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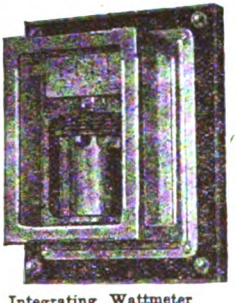

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VOL. 43. 1909. NO. 196.

Proceedings of the Four Hundred and Eighty-eighth Ordinary General Meeting of the Institution of Electrical Engineers, held in the Rooms of the Institution of Civil Engineers, Great George Street, Westminster, on Thursday evening, February 11, 1909 — Mr. W. M. MORDEY, President, in the chair.

The minutes of the Ordinary General Meeting held on Thursday, January 28, 1909, were taken as read and confirmed.

The list of candidates for election into the Institution was taken as read, and it was ordered that it should be suspended in the Library.

The following list of transfers was announced as having been approved by the Council:—

TRANSFERS.

From the class of Associate Members to that of Members:—

Edward A. Barker. | William Maurice.

From the class of Associates to that of Members:—

Cecil Barber. | Robert Orsettich.

From the class of Associates to that of Associate Members:—

Edward Geo. Anness. | Ernest A. Lambert.
Geo. K. Nowlan.

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From the class of Students to that of Associate Members—

William B. Adams.	F. E. Berry.
W. J. A. Anderson.	L. Calisch.
A. W. Barnley.	J. K. Catterson-Smith.

G. W. Stewart.

Messrs. W. W. Cook and A. D. Stevenson were appointed scrutineers of the ballot for the election of new members, and, at the end of the meeting, the following were declared to have been duly elected :—

ELECTIONS.

As Members.

Dr. Max Kloss.	Charles Stafford Schultz.

As Associate Members.

George John Leigh Brown.	John Horn Murray.
Herbert N. Calvert.	Alexander Dick Phillips.
Joseph Russell W. Grainge.	Frederick Dennis Pyne.
Arthur Stanley Hawkins.	Ernest E. Shatford.
Edward John Lincoln.	William Smith.
Harry William Moore.	Cyril Reginald Sprague.

Thomas George Wright.

As Associates.

John Singleton Green.	Harry James Simpson.

Donations to the *Library* were announced as having been received since the last meeting from Messrs. Cassell & Co., Ltd., H. R. Kempe, Messrs. F. C. & W. H. Smith, Professor R. H. Smith, Messrs. E. & F. N. Spon, Ltd.; to the *Building Fund* from R. H. Burnham, A. H. Dykes, H. W. Handcock; to the *Benevolent Fund* from F. Gill, R. K. Gray, to whom the thanks of the meeting were duly accorded.

The PRESIDENT: Before calling on the authors for their paper, I have to make an announcement with regard to the staff of the Institution. To-night, I am sorry to say, we see our friend Mr. Lloyd in his place as Secretary for the last time. He has served us ably and well for five years, and has become a friend of many of us here. The Council has appointed as his successor, Mr. Rowell, who has been the first assistant in the office for eight years, and is, no doubt, well known to you all. To-night we welcome the coming and speed the parting Secretary. Our good wishes and our goodwill go with Mr. Lloyd; and we hope and believe that Mr. Rowell will prove a worthy successor to him.

A paper (see p. 3) by Messrs. L. Andrews and Reginald Porter, entitled "The Use of Large Gas Engines for Generating Electric Power," was read and discussed.

The meeting adjourned at 9.40 p.m.

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THE USE OF LARGE GAS ENGINES FOR GENERATING ELECTRIC POWER.

By LEONARD ANDREWS, Member, and REGINALD PORTER, B.A., Associate Member.

(*Received November* 19, 1908, *read at London and Dublin on February* 11, *and at Manchester on February* 16, 1909.)

In the discussion on Messrs. Merz and McLellan's paper on "Power Station Design"* Colonel Crompton said: "I regret to say that the authors have not told us much on the question of the day, *i.e.*, the real *pros* and *cons* of plant driven by steam *versus* internal combustion engines. When I heard of the paper I had hoped that we should have had this matter fully discussed, but I regret to see that no comparison is attempted in a quantitative sense." What Colonel Crompton then somewhat prophetically referred to as the question of the day is now, nearly five years later, recognised as such by practically all engineers interested in power-station design. To-day one can scarcely pick up a technical paper that does not contain some reference to the growing use of large internal combustion engines.

Hitherto the use of large gas engines has been chiefly confined to iron and steel works, where they are run on blast furnace and other waste gases for driving blowing engines and generating electric power, which is used for rolling mills, etc., in the works, the surplus power being sold, at a very low rate, for municipal lighting and tramway loads, and for industrial works in the neighbourhood.

In Germany the manufacture of large gas engines is an established industry on a large scale. Even in 1906, out of forty-nine smelting works forty-one had either installed gas engines or had placed orders for them, the engines actually installed at that time aggregating over 295,000 H.P. †

Whilst there have been a few blast furnace gas engine installations working in this country for some years, the engines used have been mainly limited to capacities of from 300 to 500 B.H.P., and credit must undoubtedly be given to the German iron and steel industry for having created the demand which has brought the large gas engine to its present state of perfection.

The use of large gas engines for driving electric generators is a subject that is also receiving considerable attention in the United

* *Proceedings of the Institution of Electrical Engineers*, vol. 33.

† From *Science Abstracts*, January, 1907.

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States. A few months ago the National Electric Light Association appointed a special Committee to report on the use of large gas engines for driving electric generators, and the report was presented to the Association at their convention held in Chicago last May.

This report, in addition to giving very interesting descriptions of some of the large American gas engines, contains a number of tabulated replies to inquiries sent to many users of large gas engines respecting the output of the units employed, the quantity of gas, oil, cooling water, etc., used, and the nature of the troubles experienced. The tables also set out the monthly cost of repairs for each installation, and users' comments upon questions of parallel operation, continuity of service, reliability and economy as compared with steam plant, and general remarks. Whilst these most interesting and instructive replies show that in some cases troubles have been experienced, none of them appear to be of an insurmountable nature. It is encouraging to note from the general remarks column of the tables that the majority of users' comments are distinctly favourable to gas engines, both as regards reliability and economy of working.

The Committee's Report, which is very voluminous, concludes with an interesting summary, the general character of which may be gathered from the following extracts :—

> "The high thermal efficiency of the combined gas engine and producer must command the attention of all companies using fuel for power purposes, and the development of the gas engine and gas producer should, therefore, receive the careful study of all power users.
>
> "The efficiency of the combined gas engine and producer is higher than that of a combined steam plant of boilers and steam engines or boilers and steam turbines."
>
> ". . . There are to-day installed and building in this country at least 300,000 H.P. in large units. . . ." "The enormous investment as shown above indicates the assurance with which the operators of this class consider the reliability of the gas engine. . . ." "Continuous operation can be expected with no more attention than that given to steam engines of equal capacity. . . ."
>
> "While at present the Committee believes that the cost of gas engines is much in excess of that of steam engines of the same capacity, it also believes that it is possible to build a combined producer and gas engine plant for costs approximately that of the combined boiler and steam engine plant, when all auxiliaries and buildings are included."

One of the authors, during a recent visit to the States, had the good fortune to meet Mr. W. C. Eglin, the Chairman of the special Committee referred to above, and obtained much interesting information from him, and from other engineers who have studied the question, some of which is embodied in the present paper.

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Whilst the authors believe that there is an important field for the use of large gas engines for driving electric generators, they do not consider that there is at present justification for the suggestion that has been made, that the internal combustion engine will, in the early future, be used to the exclusion of the external combustion engine.

The position, so far as present knowledge goes, may be briefly summarised as follows :—

The internal combustion engine is very much more economical than any external combustion engine yet known.

The capital cost of a gas engine and producer installation is greater than that of a steam turbine and boiler installation of equivalent overload capacity.

There is no material difference in the reliability or in the cost of labour, stores, and repairs of the respective systems.

In cases, therefore, where the cost of fuel is low, and the load factor is low, it will generally be a mistake to use gas engines. On the other hand, where the load factor is high, or the cost of fuel is high, there can be no doubt that gas engines will prove to be by far the cheapest prime mover to employ for driving electric generators.

The majority of cases to be dealt with will doubtless fall between these two extremes, and engineers responsible for the design of future power houses will have many points to consider before definitely deciding whether the prime movers for the electric generators shall be steam or gas driven, or a combination of the two.

As the conditions which go to determine whether gas engines should, or should not, be used are in most cases so widely different from the conditions under which experience has, up to the present, been obtained, it is extremely difficult for engineers to utilise the available knowledge upon the subject to the best advantage.

We have, therefore, endeavoured to collect facts from a large number of different sources, and to apply the information obtained to one or two hypothetical public electric supply schemes as nearly comparable as possible with many of the existing power supply schemes that are now being carried out in different parts of the country.

For comparative purposes we have endeavoured to show what, in our opinion, would be the respective total cost of generating power by steam turbines and by gas-driven generators under the assumed conditions specified.

To enable engineers who have had experience both with gas installations and with steam installations to criticise our estimates, we have given somewhat full details of our calculations, and, to some extent, the source of information upon which these are based.

For the first scheme to be considered we have assumed that the estimated maximum load to be dealt with shall be 8,000 k.w.

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That the overload and standby capacity of the plant shall be such as to carry the maximum load of 8,000 k.w. for at least two hours, should any portion of the plant break down at the time when one unit is already laid off for overhaul.* (It is felt that this method of expressing the capacity of standby required is far more satisfactory than doing so in terms of percentage overload, as the useful value of the latter depends largely upon the number and size of the units employed.)

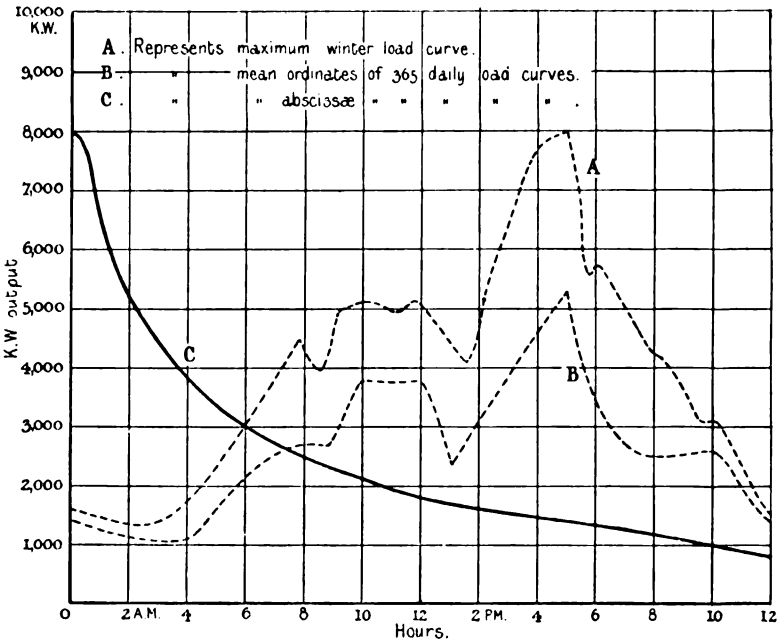

FIG. 1.

That the power generated is utilised for public and private lighting, and for a tramway and general industrial motor load; that the load factor—*i.e.*, $\frac{\text{units sold} \times 100}{\text{maximum demand} \times 8760}$, equals 24 per cent., and that the efficiency of distribution—*i.e.*, $\frac{\text{units sold} \times 100}{\text{units generated}}$, equals 80 per cent., and that the mean daily load curve is approximately of the shape shown in B, Fig. 1.

That the cost of good bituminous slack, having a calorific value of 13,000 B.Th.U. per lb. is 12s. per ton delivered at the generating station.

* As recommended by Mr. Bernard Jenkins in the discussion on Messrs. Merz and McLellan's paper.

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Choice of Site.—The points to be considered in selecting a site for a gas-driven station are practically the same as for a steam-driven station, viz. :—

A. A plentiful supply of water for cooling purposes.
B. Transport of fuel.
C. Suitability of site relatively to position of centre of distributing area, as affecting cost of feeders.
D. Liability of nuisance to adjoining property.
E. Cheapness of land.
F. Cost of constructing foundations for plant, buildings, and chimneys.

In choosing a site for a steam turbine station it is often good policy to sacrifice other advantages in order to get a site with a plentiful supply of cold water for condensing purposes. This advantage has usually, however, to be heavily paid for. As the latitude in the choice of a site is very limited, the cost of land will probably be very much greater. The cost of foundations will also generally be greater, added to which the right of using the water will generally have to be paid for; and, finally, it is more than probable that the site available will not be a good one from the point of view which American engineers term "the electrical centre of gravity"—that is to say, the cost of feeders will probably be much greater than if a more central position were selected. It is consequently often very much cheaper, on the whole, to put down cooling towers for condensing purposes.

Inasmuch as it is impossible to estimate the cost of obtaining a site with a plentiful water supply, as this will vary largely in every case, we have based our comparisons upon the assumption that cooling towers will be used in conjunction with a public water supply.

We will assume that a convenient piece of land has been secured, bounded on one side by a railway track and on the other side by a roadway, the width of the land being 325 ft., and the length being ample to allow for all probable future extensions.

A convenient lay-out for the steam plant will be that shown in Figs. 2 and 3. Figs. 4 and 5 show a corresponding lay-out for the gas plant.*

Either lay-out provides ample yard space, room for cables, stores, etc., without encroaching on the ground available for future extensions.

Type of Generating Plant.—For the steam plant we have assumed that steam turbines of the horizontal type would be used directly coupled to 3-phase generators—that each turbine would exhaust into a separate contra-flow surface condenser placed directly below the turbines; that the cooling water would be obtained from a town supply and circulated by electrically driven centrifugal pumps through natural draught cooling towers, a separate pump being installed for each unit.

* We have shown natural draught cooling of the usual dimensions in Figs. 2 and 4, but since these plans were made we have been advised by the Midland Engineering Company that their Zylberlast Cooling Towers only occupy two-thirds of the space shown for the same capacity. If, therefore, these towers were used the space occupied by the cooling towers for both steam and gas plants would be reduced by this extent.

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For the gas plant we have assumed that the engines would be of the slow-speed, 4-cycle double-acting tandem type, directly coupled to

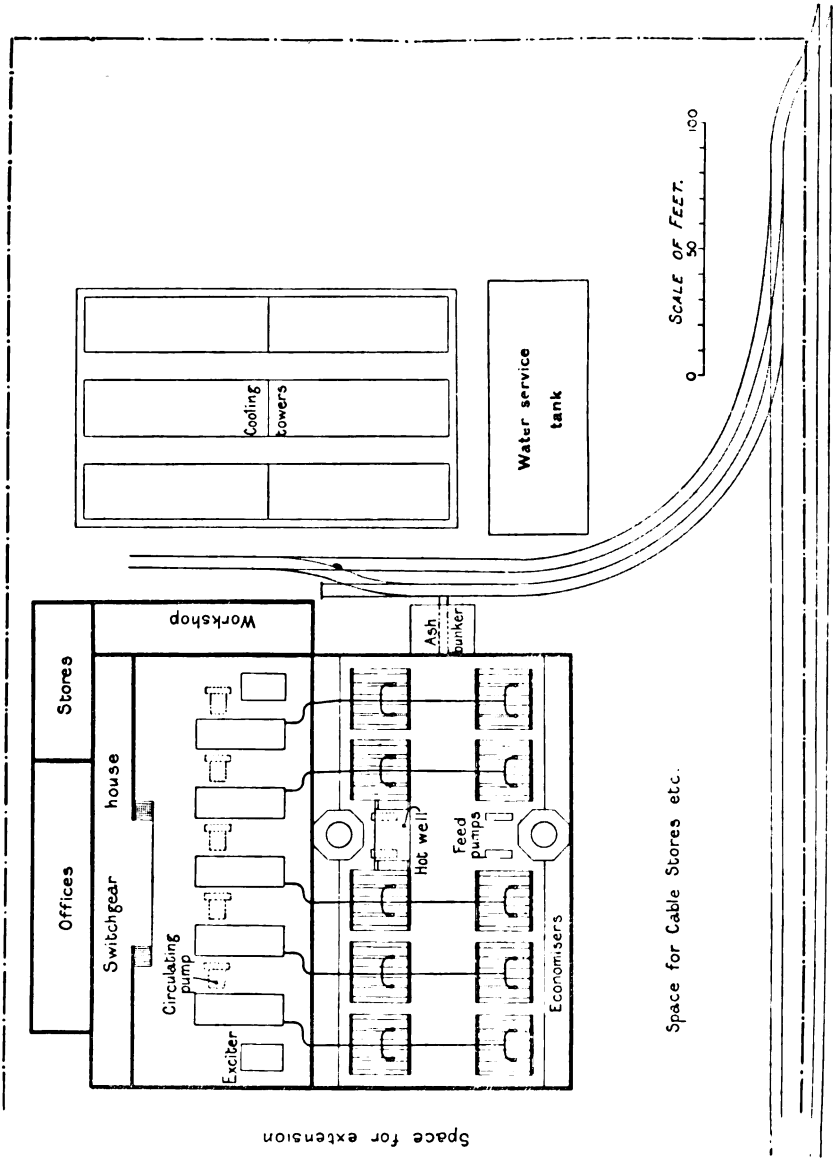

FIG. 2.—10,000-k.w. Steam Plant (Plan).

overhanging flywheel 3-phase generators. The cooling water for the engines would, as in the case of the steam plant, be obtained from

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a town supply and circulated by means of small piston pumps driven from the engine crankshafts, the water being cooled in natural draught cooling towers.

Capacity of Generator Units.—Experience has shown that large units in steam plant are considerably more economical, both in first cost and

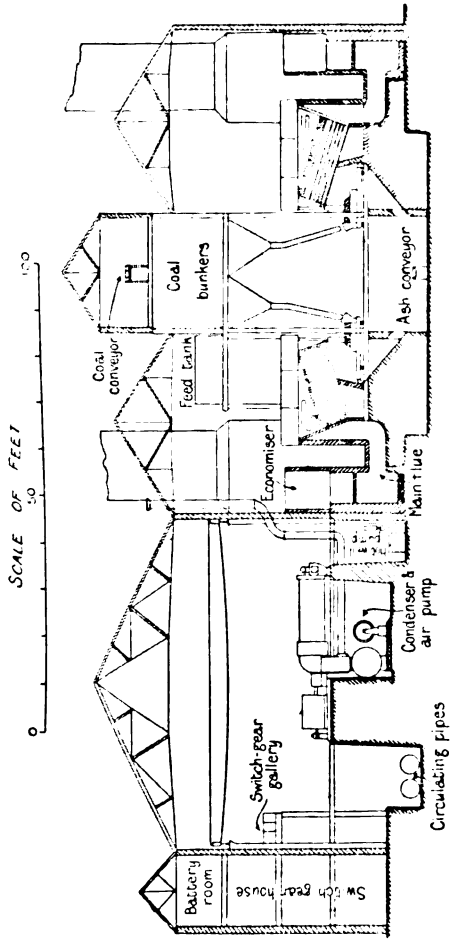

FIG. 3.—10,000-k.w. Steam Plant (Elevation).

(Scale $\frac{1}{8}$ in. to 1 ft.)

running cost, than smaller units, and as they can at present be obtained in much larger sizes than gas engines, they have, in some cases, a considerable advantage in this respect. It is possible, for instance, to obtain units of such a size that one plant would be capable with its overload capacity of supplying the specified maximum output of 8,000 k.w.

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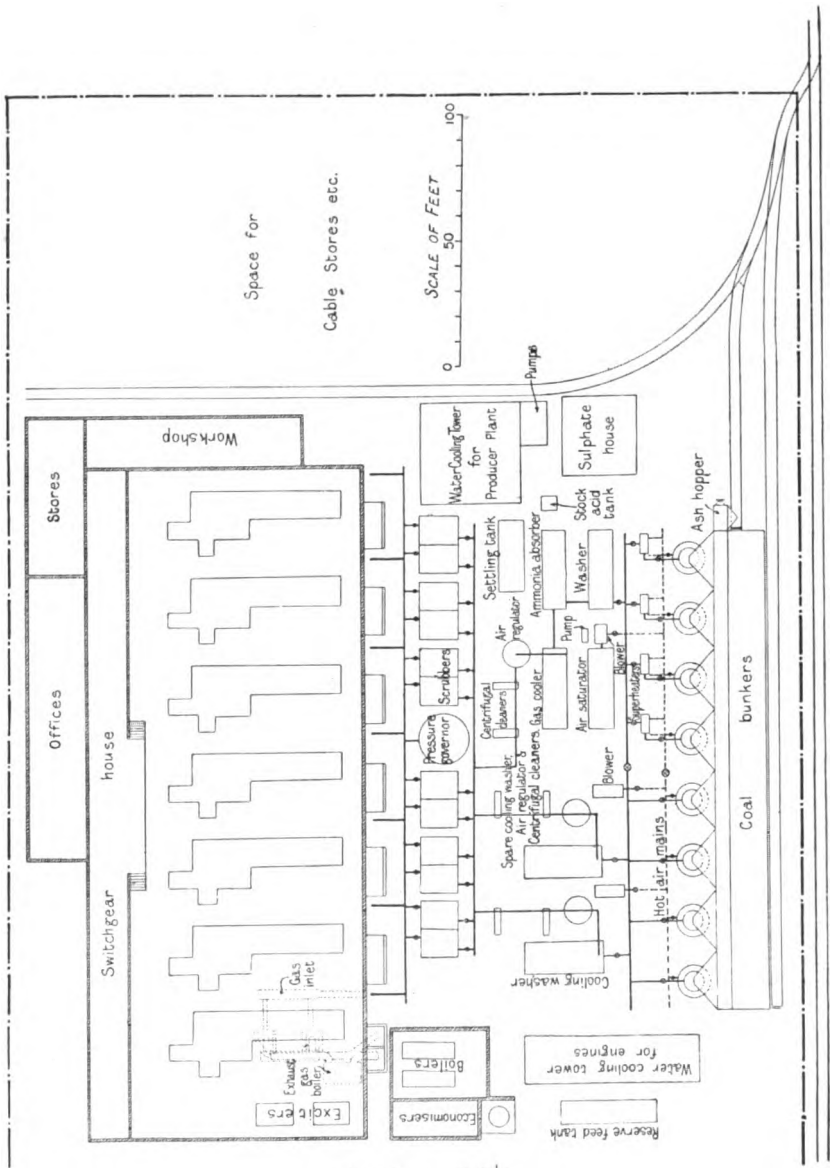

FIG. 4.—10,000-k.w. Gas Plant (Plan).

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To comply, however, with the suggested specification as to overload capacity, it would be necessary to put down two additional units of the same size, with the result that the standby capacity would be altogether out of proportion to the maximum demand, and the first cost would be considerably greater than if smaller units were selected.

For a maximum output of 8,000 k.w. it appears that the most economical arrangement of units would be five plants, each having a normal capacity of 2,000 k.w., with an overload capacity for two hours of 33⅓ per cent. In the event of two plants being laid off simultaneously, the remaining three sets would then be capable of supplying the maximum demand for a period of two hours as specified.

The output of gas-engine units is, at present, limited to about 1,500 B.H.P. per cylinder, this being the largest size that has yet been made. Four such cylinders arranged in twin tandem would give a combined output of 6,000 H.P., or, say, 4,000 k.w.

The arguments against the use of very large steam units for the hypothetical case under consideration also apply to gas-driven units. In fact, for the gas scheme it does not appear to be advisable to use even such large units as 2,000-k.w. sets, since the overload capacity of gas engines is only 10 or 12 per cent., and consequently three

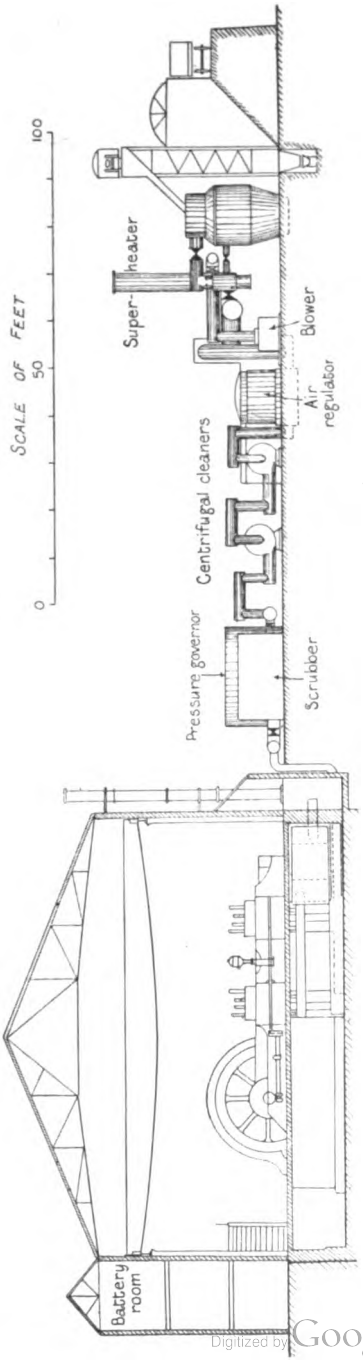

FIG. 5.—10,000-k.w. Gas Plant (Elevation).
(Scale ⅛ in. to 1 ft.)

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2,000-k.w. plants would only be able to deal with a maximum demand of 6,600–6,700 k.w., and six units of this capacity would therefore be required to deal with the specified maximum demand and provision for standby. A more economical installation would be seven generators, having a normal capacity of 1,450 k.w. each, and an overload capacity of 1,600 k.w. With such an installation if two generators were laid off simultaneously the remaining generators would be able to deal with the full maximum demand of 8,000 k.w. for two hours as specified.

Single-tandem versus *Twin-tandem Combinations.*—The next point to be determined is whether the engines should be of the single-tandem or twin-tandem type. The only advantage of the twin-tandem over the single-tandem combination appears to be that, with a 4-cycle engine, the crankshaft will receive four impulses per revolution instead of two. It is obvious, therefore, that with a given flywheel effect the cyclic irregularity will be considerably greater with the latter than with the former.

To illustrate the difference in cyclic irregularity between a double-acting single-tandem engine and a double-acting twin-tandem engine as compared with the difference between that of a double-acting tandem engine and of a single-acting engine, we have constructed curves showing the speed variation throughout each cycle of different types of engines of a given horse-power, and fitted with flywheels of a given moment of inertia.

These curves are shown in Fig. 6 for the following engines:—

750-B.H.P. double-acting twin-tandem engine showing cyclic irregularity of 1/2500.
750-B.H.P. double-acting single-tandem engine showing a cyclic irregularity of 1/250.
750-B.H.P. single-acting tandem engine showing a cyclic irregularity of 1/16·5.
750-B.H.P. double-acting single-cylinder engine showing a cyclic irregularity of 1/11.

The basis on which these curves are worked out is given in Appendix A.

Of course, in practice a very much smaller flywheel effect would be used for the twin-tandem engine, and a very much greater flywheel effect for the single-cylinder engine.

Fig. 7 shows the respective flywheel effects required with the different types of engines referred to, to maintain the cyclic irregularity within 1/250, this being the maximum variation under which generator makers usually guarantee satisfactory parallel running.*

* The large gas engines at the Bruckhausen, Homecourt and Heinitz installations, visited by English engineers in August last, are all provided with flywheels to maintain a cyclic irregularity within 1/250. The two former are single tandem engines, and the latter twin tandem, but no appreciable difference in the parallel running was noticeable.

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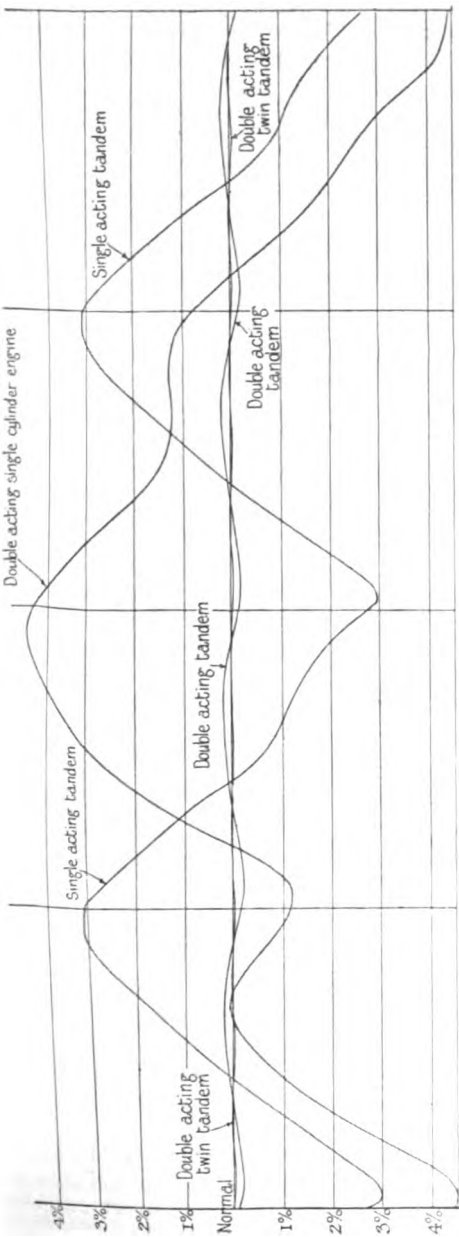

FIG. 6.—750-B.H.P. Speed Curves, showing per cent. Variation above and below Normal when fitted with a Flywheel constructed for a Tandem Double-acting Engine having a Speed Variation of 1/250.

Double-acting twin tandem	...	...	0·02 per cent.
Double-acting single tandem	...	...	0·2 "
Single-acting tandem	...	...	3·1 "
Double-acting single cylinder	...	...	4·5 "

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We have plotted in Fig. 8 curves showing the approximate capital cost of engines and generators erected complete with pipework, foundations, and flywheels necessary for the above specified cyclic regularity

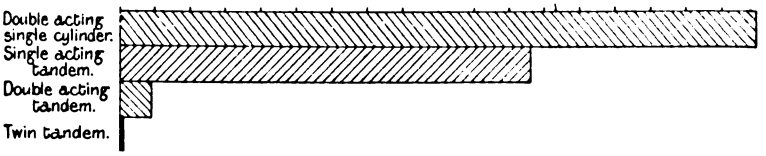

FIG. 7.—The Flywheel Effect necessary to ensure Cyclic Irregularity not exceeding 1/250.

for both single- and twin-tandem engines of outputs varying from 500 to 5,000 B.H.P.*

These curves show that the capital cost of a twin-tandem set is appreciably higher than a single-tandem set of the same output. The

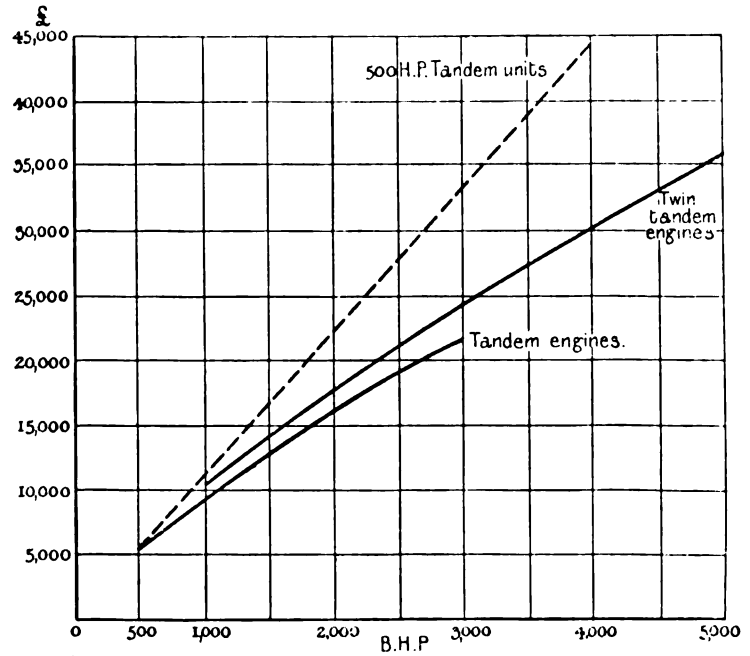

FIG. 8.—Capital Costs of Slow-speed Horizontal Gas Engines.

cost of fuel, oil, and repairs will be slightly higher for the twin-tandem combination, though not appreciably so. The cost of driver's wages for the twin-tandem will be practically double that of the single-tandem

* A curve is also plotted showing the corresponding capital charges for an equivalent output generated by a number of 500-H.P. units in parallel.

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set, as experience has shown that one engine-driver is required for each line of engines, whatever the output of the engines.*

It appears, therefore, that for the conditions under discussion a single-tandem engine is the best type of plant for the purpose.

Boilers for Steam Plant.—We have assumed that boilers of the water-tube type would be used, fitted with self-contained superheaters and automatic stokers, and that these boilers would be grouped into units corresponding to the output of the turbo-generators, as recommended by Messrs. Merz and McLellan and other designers, the normal capacity of each battery of boilers being equal to that of the normal output of its turbo-generator. In calculating the boiler capacity we have assumed that the steam consumption of the turbo-generator under working conditions, including the steam for feed-pumps and exciters, would be 20 lbs. per kilowatt generated. We have therefore provided for four 10,000-lb. boilers for each 2,000-k.w. turbine.

In order to keep the boiler house about the same length as the engine-room we have provided two rows of ten boilers, grouped in five batteries of four boilers.

An economiser is provided for each group of boilers.

Producers.—It is gratifying to record that whilst the development of large gas engines has been more pronounced in Germany than in this country, England can boast that it has done much more in perfecting the producer end of the problem.

From inquiries made both in Germany and the United States, it would appear that large producers for utilising bituminous coal have not been entirely satisfactory in either of these countries. This is, perhaps, partly accounted for by the fact that the class of coal available in both these countries contains a far greater percentage of ash and is much more liable to clinker than the bituminous coal available here. Whatever the cause may be, the fact remains that there are numbers of bituminous producer installations in this country working entirely satisfactorily in conjunction with large gas engines.

One firm of English producer makers alone have at the present time various plants supplying gas to large engines having an aggregate output of over 90,000 B.H.P. From information obtained from users, it appears that these producers are giving entire satisfaction.

With properly designed engines there appear to be no greater difficulties to contend with than when working on blast-furnace gas. The comparatively high percentage of hydrogen tends to cause pre-ignition if the compression is carried to too high a point. This difficulty is, however, entirely removed by constructing the engines for a lower compression.

* These remarks apply to cases where the total maximum demand is insufficient to justify the use of larger units than can be obtained in single tandem sets. Where the total output is so great that the failure of, say, a 4,000-k.w. plant will not seriously cripple the undertaking or involve the provision of abnormal standby charges, the first cost of a twin-tandem gas plant will be considerably less than that of two single-tandem sets of corresponding output. Saving will also be effected on capital cost of flywheels, generators, foundations, and buildings.

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Difficulties were experienced in the early days in the removal of tar, dust, and other impurities, but the efficient cleaning appliances now included in every properly constructed producer plant appear to have entirely got over these difficulties, or have at least reduced them to such an extent that the small percentage of impurities carried into the engine with the gas has no deleterious effect upon the working of the engine.

Difficulties arising from variations in the quality of the gas caused by charging or clinkering the producers practically disappear when a number of producers are connected together to feed into a common main or common receiver where the gases from the various producers are mixed together, and the effect of any variation in the quality of the gas from individual producers is thereby neutralised. To derive the full benefit of this feature the producer plant should not be divided into units corresponding to the generator units, as has been recommended for steam boilers.

Sulphate of Ammonia Recovery Plants.—A very important point to be considered in designing a gas-engine station is that of providing for the recovery of sulphate of ammonia.

There are numbers of recovery plants that have been working for some years where the sale of the by-product has almost equalled the cost of the fuel used. Results obtained have been so entirely satisfactory that one is at first sight tempted to think it must pay to provide for sulphate of ammonia recovery in every instance. There are, however, many expenses incidental to the recovery of sulphate of ammonia in addition to the fuel.

The following points must be taken into consideration as affecting the use of ammonia recovery plants :—

1. The first cost of the recovery plant, particularly for small sizes, is very much greater than the first cost of non-recovery plant.
2. Some extra labour is involved in operating the plant.
3. The purchase of sulphuric acid, of which approximately 1 ton is required for every ton of sulphate of ammonia turned out, is quite a heavy item.
4. The yield of heat units per ton of coal is slightly less if sulphate of ammonia is recovered than the yield from non-recovery plants.
5. The extra cost of repairs and the cost of handling and packing the by-product absorb some of the profits effected by the recovery process.

Experience, up to the present, appears to indicate that it is not worth while to attempt to recover sulphate of ammonia unless the total output of the plant is greater than 2,000 H.P., and then only on an exceedingly good load factor.

For a maximum output of 8,000 k.w. it would probably pay to put down ammonia recovery plant, even for so poor a load factor as 24 per cent. An even more profitable arrangement, however, would be to

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provide for ammonia recovery on one portion of the plant, which could be kept working at a very high load factor almost continuously, and to use non-recovery plant for dealing with the peak load and remaining portion of the total output.

For the particular conditions now under discussion, the Power Gas Corporation (to whom we are indebted for this suggestion) recommend the use of eight producers, of which four would be equipped for ammonia recovery and the remaining four for non-recovery.

Coal-handling and Storing.—For both the steam and gas plants we have assumed that coal bunkers will be provided capable of carrying a fortnight's consumption of fuel under mean load conditions.

In the case of the steam plant we have assumed that the coal bunkers would be placed over the firing floor of the boilers. These bunkers would have a capacity of 1,500 tons.

In the case of the gas plant the coal would be stored in bunkers placed on the ground at the back of, and parallel with, the producers. It would be unloaded by hand from the railway trucks on the elevated siding at the back of the bunkers, from which it would gravitate into the coal-conveyor buckets and be hoisted by these into the hoppers over the producers. These hoppers would be of sufficient capacity to carry 24 hours' supply under mean-load conditions. The ashes raked out from below the producers would also be lifted by the same conveyor into the ash hopper provided for the purpose. A sectional elevation of one of the producers with the coal- and ash-handling arrangements used is shown in Fig. 9.

Building and Foundations.—The cost of the engine-room and engine foundations for the gas-driven plant is, of course, considerably greater than that of the steam plant, but no building is required for the producers (beyond small boiler and sulphate houses), and the cost of the foundations for the producers is very small compared with the cost of boiler foundations, flues, chimneys, etc. The total cost of buildings amounts to considerably less, therefore, for the gas station than for the steam station.

We have based our estimate of the cost of buildings for the gas-driven plant upon tenders actually received. The price covers a substantial steel-frame building with brick walls, lined internally with a glazed brick dado 6 ft. high, and with tiled engine-room floor.

We have included suitable store, workshop, and office accommodation in each case.

Exciting Plant, Switchgear, etc.—We have assumed that for both the steam plant and the gas plant the field circuits of the generators would be excited from busbars fed by two steam-driven exciters, each capable of generating the whole of the exciting current required on full load. The exciters would be supplemented by a battery capable of maintaining the full field current required for a period of twenty-four hours.

In the case of the gas plant the steam for the exciters would be furnished by one of the small coal- or tar-fired boilers installed for this

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purpose. The exhaust steam from the exciter engines would be used in the producers, any additional steam required by the latter being raised by boilers heated by the exhaust gases from the main engines.

The switchgear would be of the remote control type, the oil-break switches being placed in a switch-room running the length of the engine-room.

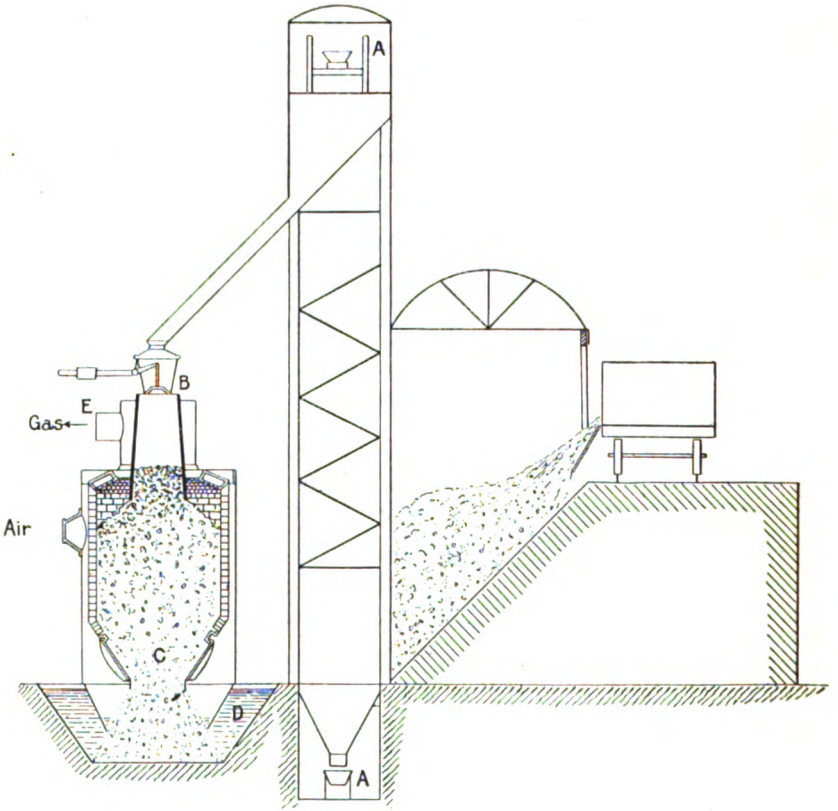

FIG. 9.

The capital cost of the switchgear for the gas plant will be somewhat higher than for the steam plant, as two additional generator panels and connections will be required.

Capital Outlay.—The total capital cost of the respective steam and gas plants for the specified maximum load of 8,000 k.w. will, we estimate, be as follows:—

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Steam Plant.

	£	s.	d.
Five 2,000-k.w. turbo-generators, erected complete ...	39,500	0	0
Five surface condensers with air and circulating pumps	9,875	0	0
Circulating pipes	1,200	0	0
Cooling towers erected complete	6,900	0	0
Twenty water-tube boilers erected complete with mechanical stokers, economisers, superheaters, feed pumps, water service tank and feed tank, water softening plant and all pipe work ...	31,300	0	0
Buildings with engine and boiler foundations, two chimneys and flues	33,600	0	0
Overhead travelling crane...	1,000	0	0
Steel structural work, coal bunkers, coal and ash conveying plant	8,900	0	0
Exciters, battery, switchgear, and connections to generator	7,250	0	0
	£139,525	0	0

Or £13·952 per kilowatt installed.

Gas Plant.

	£	s.	d.
Seven 1,450-k.w. gas engines, generators, air compressors, gas, water, air, and exhaust pipes and all auxiliaries erected complete	98,000	0	0
Four ammonia-recovery producers, erected complete with superheaters, blowers, cooling and washing towers, centrifugal cleaners, scrubbers, ammonia absorber, and all pipe-work	18,490	0	0
Duplicate blower, washer, and centrifugal cleaners ...	3,780	0	0
Four non-recovery producers with necessary scrubbers, etc.	10,340	0	0
Steam-raising plant, economisers, feed-pumps, etc. ...	4,850	0	0
Water cooling towers, pumps, and water softener ...	1,990	0	0
Buildings and foundations, etc.	24,275	0	0
Overhead travelling crane	1,250	0	0
Steel structural work, coal bunkers, coal and ash conveying plant	6,150	0	0
Exciters, battery, switchgear, and connections to generators	7,750	0	0
	£176,875	0	0

Or £17·68 per kilowatt installed.

Operation of Gas Plant.—As there are probably many engineers interested in the design of power stations who are not familiar with the

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method of operating a combined producer and gas-engine station, a few words on this subject may not be out of place before considering the comparative running cost of the respective systems.

The coal is fed by means of the endless chain elevator A A (Fig. 9) into the bunkers above the producers, from which it gravitates through the valve B into the producer C. The ashes are regularly withdrawn through the water lute D every four hours, the quantity being determined by the rapidity of combustion in the producer.

The hot gases escaping from the outlet E at the top of the producer pass into the superheater, which consists of a series of vertical pipes surrounded by the steam and air passing on their way to the producer. A considerable portion of the sensible heat is herein extracted and utilised.

The gas then passes to the mechanical washer, where it is treated with a spray of warm water thrown up by revolving paddle-wheels. The dust and soot in the gas are by this means removed and the temperature of the gas considerably reduced. The warm water is also at the same time heated up and passed to the air saturator, in which, by heating and saturating the air on its way to the producer, it is cooled for further use in the washer.

Passing from the washer, the gas next enters the mechanical ammonia absorber, where it meets a fine spray of a solution of sulphate of ammonia, which contains a small amount of free sulphuric acid. In this apparatus the acid in the solution combines with the ammonia in the gas, producing sulphate of ammonia. The acidity of the liquor is kept up by a small trickle of sulphuric acid into the absorber; the sulphate liquor, which is continually being augmented in volume by the new sulphate of ammonia formed, slowly and continuously trickles out of the absorber to the stock liquor tanks.

Following the passage of the gas, it is next treated in a mechanical gas cooler, where it meets a spray of cold water, and where it gives up the bulk of its tar. The gas leaving this cooler passes to the air regulator, which is merely a small gas-holder, the height of which regulates the quantity of air supplied by the blowers. Thence the gas passes through two centrifugal cleaners in series, which, revolving at high speeds and in conjunction with a small amount of injected water, effectually remove all but very small traces of the tar contained. These latter are removed by passing through the sawdust scrubbers, whence it emerges in a thoroughly cool and purified condition and enters another gas-holder, which serves to keep a constant pressure in the supply main to the gas engines.

The non-recovery process (the apparatus for which is shown on the left of the general lay-out drawing, Fig. 4) is very much simpler. The gas, in this case, passes direct into the cooling washer and from this, through the gas regulator and centrifugal cleaners to the scrubbers and engines. It will be noted that a spare blower, washer, regulator and centrifugal cleaner are provided, which may be used either for the non-recovery producers on the left, or for the recovery producers

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on the right. In the latter case, the recovery producers become non-recovery producers.

Running Cost.—The fuel consumption of a gas plant, as of a steam plant, is dependent upon at least four important factors:—

1. The actual output, which in an electric generating plant will be expressed in kilowatt-hours generated.
2. The no-load losses, which include friction, windage and electrical losses incurred in running the generator on open circuit, together with all power required for exciters, pumps, and other auxiliaries.
3. Standby losses of banking boilers or producers.
4. The ratio of the actual ascertained fuel consumption under day by day working conditions to the theoretical consumption based upon test results applied to items 1, 2, and 3, which we will term the discrepancy factor.

The steam and fuel consumption curves, shown in Fig. 10, have been plotted from a number of published tests of steam turbines and gas engines of different sizes. The ordinates above the zero line represent the steam and fuel utilised for the actual generation of electric power, whereas those below indicate the fuel required per hour to run the generators at full E.M.F. on open circuit. The former are approximately proportional to the units generated and are practically independent of the hours the plant is run, whereas the latter are approximately directly proportional to the hours the plant is run and are not appreciably affected by the units generated. It will be noted that the slope of the "consumption per unit generated" curves of steam turbines gradually decreases as the output of the plant is increased, whereas the corresponding curve of gas-driven generators is constant for all outputs. Various tests on gas engines of outputs ranging from 500 B.H.P. to 5,000 B.H.P. show that the actual consumption of fuel per unit generated exclusive of no-load losses is approximately 1 lb. per kilowatt-hour for any output from no load to full load.*

The 6,000-k.w. steam turbine curve is plotted from the recently published tests of a 6,000-k.w. turbo-generator at Manchester. The total steam consumption at full load was 95,000 lbs., or 15·9 lbs. per unit generated, exclusive of steam for exciters and auxiliaries. The characteristic of the steam consumption curve at lighter loads appears to indicate that the no-load consumption of the plant would be approximately 15,000 lbs. of steam per hour. We have therefore plotted the no-load consumption of 15,000 lbs. below the zero line, and the balance of 80,000 above the zero line, which gives a steam

* Mr. Bibbins, *Proceedings of the American Institution of Electrical Engineers*, vol. 27, found on a recent test of a complete 400-k.w. gas engine and producer plant that the fuel consumption on full load was 600 lbs., of which he estimated one-third was utilised for auxiliaries and for other no-load losses. The fuel consumed in generating current was therefore $\frac{(600) - (200)}{(400)} = 1$ lb. per unit generated.

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consumption per actual unit generated of 13·4. To the no-load ordinates below the zero line, we have added the estimated steam consumption of exciters, air and circulating pumps, feed pumps and all other auxiliaries, which we have taken at 6 per cent. of the total full-load steam consumption, and from this second curve we are able to ascertain the no-load losses of any size of plant.

The corresponding curve, showing the no-load losses of gas engines with all auxiliaries, is also plotted below the zero line.

Standby Losses.—The losses, through radiation of heat from boilers and steam pipes, and by leakage of cold air through the brickwork of boilers, are a very heavy item in all steam-driven electric generating stations, as the conditions of load are generally such that the majority of the boilers are banked for many hours every day.

Colonel Crompton found that the fuel required for banking a boiler at the Chelmsford Electric Light Works, rated at 4,200 lbs., amounted to 67 lbs. per hour, or 16 lbs. of coal per hour per 1,000 lbs. of steam evaporated.*

Mr. Collings Bishop, of Newport, found that two boilers, each rated for an evaporation of 10,000 lbs. per hour, require 224 lbs. of coal per hour for banking = 11·2 lbs. of coal per hour per 1,000 lbs. of steam.*

As four 10,000-lb. boilers are required for each 2,000-k.w. unit in connection with the steam turbine station on which we have based our calculations, the coal for banking these boilers will be at least 448 lbs. per hour per plant unit.

The fuel required for banking producers is only a small fraction of that required for banking boilers. The heat radiation from the producer is also extremely small, because the annular space between the fire-brick lining and the outer casing constitutes one of the best non-conductors of heat it is possible to obtain.

The standby losses of the producers for the scheme under consideration are guaranteed not to exceed 50 lbs. per hour per producer.

Discrepancy Factor.—It is difficult for those who have not had actual experience in running a generating station to appreciate how impossible it is to keep this factor within reasonable limits. This is accounted for by variations in the quality of the fuel supplied, by fuel utilised in heating up cold boilers, by the gradual fouling of boiler tubes, condenser tubes, etc., between cleaning periods, by errors of judgment as to the correct time for running up and shutting down plant units, and other seemingly small details which in a well-managed station receive constant attention, but the effects of which cannot be entirely eliminated.

For both the steam plant and the gas plant we have added 25 per cent. to the ascertained fuel consumption under test conditions to cover the above contingencies.

Now, for a maximum demand of 8,000 k.w. a load factor of 24 per cent. and a distribution efficiency of 80 per cent., the units generated per annum will be 21,000,000. The curves in Fig. 10 show that for a

* Dowson and Larter, "Producer Gas."

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2,000-k.w. turbo-alternator the steam consumption per unit generated is 15·5 lbs., or, assuming an evaporation of 8 : 1, 1·94 lbs. of coal. From the same curves we see that the no-load losses for a plant of this size amount to 900 lbs. per hour.

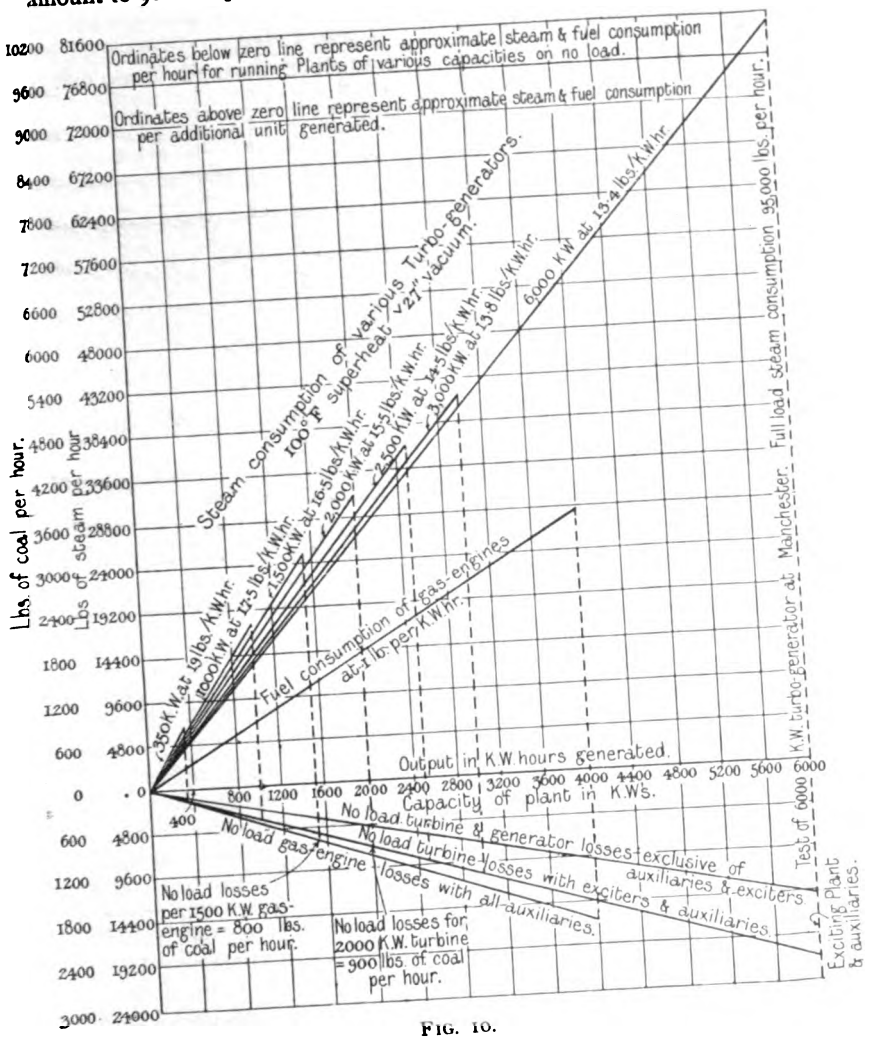
Ordinates below zero line represent approximate steam & fuel consumption per hour for running Plants of various capacities on no load.
Ordinates above zero line represent approximate steam & fuel consumption per additional unit generated.
Steam consumption of various Turbo-generators. 100° F superheat. 27" vacuum.
6000 K.W. at 13·4 lbs./K.W.hr.
3000 K.W. at 14·5 lbs./K.W.hr.
2500 K.W. at 15·5 lbs./K.W.hr.
2000 K.W. at 16·5 lbs./K.W.hr.
1500 K.W. at 17·5 lbs./K.W.hr.
1000 K.W. at 19 lbs./K.W.hr.
350 K.W. at 19 lbs./K.W.hr.
Fuel consumption of Gas-engines at 1 lb. per K.W.hr.
Lbs. of coal per hour.
Lbs. of steam per hour
Output in K.W. hours generated.
Capacity of plant in K.W's.
No load turbine & generator losses exclusive of auxiliaries & exciters
No load turbine losses with exciters & auxiliaries
No load turbine losses with all auxiliaries.
No load losses per 1500 K.W. gas-engine = 800 lbs. of coal per hour.
No load losses for 2000 K.W. turbine = 900 lbs. of coal per hour.
Test of 6000 K.W. turbo-generator at Manchester. Full load steam consumption 95,000 lbs. per hour.
Exciting Plant & auxiliaries.

FIG. 10.

To determine the plant-unit-hours run and the boiler-hours banked, we have reproduced curve C Fig. 1, and have plotted in Fig. 11 the average hours the respective plant units would be required each day to deal with the given load curve.

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It appears that the minimum total engine-hours would be 35 hours per day, or 12,800 hours per annum, and the banked boiler-hours would be 45 hours per day or 16,800 hours per annum.

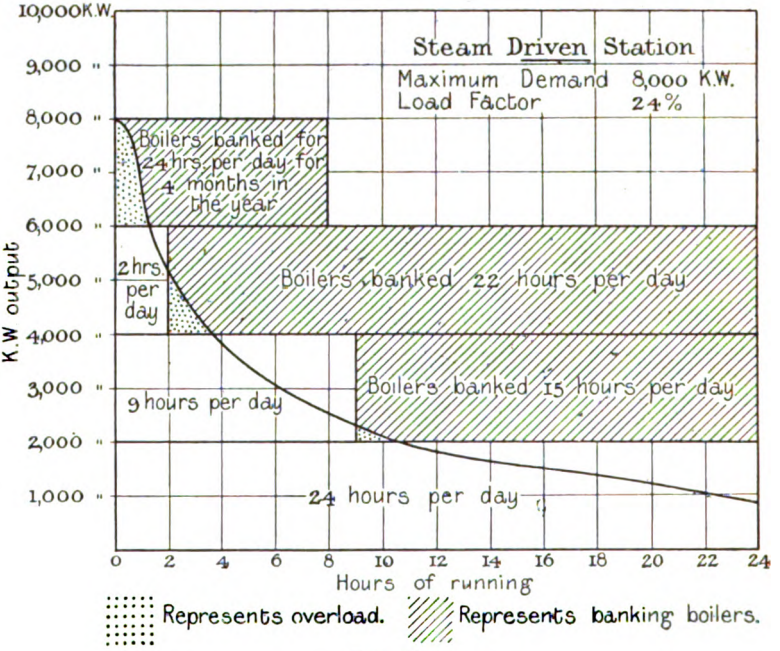

FIG. 11.

The total annual coal consumption for the steam turbines will therefore be as follows :—

21,000,000 units at 1·94 lbs.	18,170	tons.
12,800 engine-hours at 900 lbs.	5,140	,,
16,800 banked boiler-hours at 448 lbs....	3,330	,,
	26,640	,,
Discrepancy factor (1·25) ...	1·25	,,
Total ...	33,300	tons.

= 3·55 lbs. per unit generated.

Overall thermo-dynamic efficiency = 7·4 per cent.*

* Since the above estimates were prepared, we have obtained actual fuel consumption results, taken over a considerable period, at a number of modern steam and gas installations, which we have embodied in the Table of Efficiencies, Appendix C. It will be noted that the actual mean thermal efficiency of the steam station returns is 6·7 per cent., or 10 per cent. less than our estimate based on the above theoretical conclusions. Whereas the actual gas installations show a mean efficiency of 13·7 per cent., or 10 per cent. greater than our estimate.

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For the gas station we see upon again referring to Fig. 10 that the no-load losses of a 1,500-k.w. gas engine amount to 800 lbs. of coal per hour and the useful output consumption to 1 lb. per unit generated.

Fig. 12 shows the minimum average engine-hours per day for the gas plant and the average hours per day the producers would be banked. It appears from this that the total engine-hours would be 17,450 hours per annum, and banked producer-hours would be 35,000 hours per annum.

The total coal consumption for the gas plant will therefore be as follows :—

21,000,000 units at 1 lb. coal	9,360	tons
17.450 engine-hours at 800 lbs.	6,230	„
35,000 banked producer-hours at 50 lbs.	782	„
	16,372	„
Discrepancy factor (1·25) ...	1·25	„
Total ...	20,465	tons.

= 2·18 lbs. per unit generated.

Overall thermo-dynamic efficiency = 12 per cent.*

It is estimated that approximately 71 per cent., or 14,580 tons, of the total coal consumption would be gasified in the ammonia producers, and would yield at least 586 tons of sulphate of ammonia. Estimating the value of this at £11 per ton, which is considerably less than its present market value, the sale of this by-product would yield £6,446 per annum.

One ton of sulphuric acid, costing 30s. per ton, is required for each ton of sulphate of ammonia ; bags cost 5s. per ton, and the cost of handling and packing the ammonia is estimated at 1s. 6d. per ton. The cost of acid, bags, and packing will therefore be £1,070, reducing the total amount to be credited on account of sale of sulphate of ammonia to £5,376.

Oil, Waste, and Stores.—The cost of oil for the steam turbine plant is estimated at 0·003d. per kilowatt-hour generated. This figure, which, it is thought, is considerably below the average oil consumption in steam turbine generating stations, is based upon a figure given in Messrs. Parsons, Stoney, and Martin's paper on " Steam Turbines."

The oil consumption for large gas-driven generators is stated, by different authorities, to be from 0·2 to 0·37 gallons per 1,000 H.P.-hours, the average cost of the oil used being 1s. 6d. per gallon.

* Since the above estimates were prepared, we have obtained actual fuel consumption results, taken over a considerable period, at a number of modern steam and gas installations, which we have embodied in the Table of Efficiencies, Appendix C. It will be noted that the actual mean thermal efficiency of the steam station returns is 6·7 per cent., or 10 per cent. less than our estimate based on the above theoretical conclusions. Whereas the actual gas installations show a mean efficiency of 13·7 per cent., or 10 per cent. greater than our estimate.

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Taking the higher figure, the oil consumption per plant unit will be 0·74 gallons per hour, or ... ... £970 per annum.

The cost of the oil for the auxiliary plant is estimated at ... 200 „ „

£1,170 per annum.

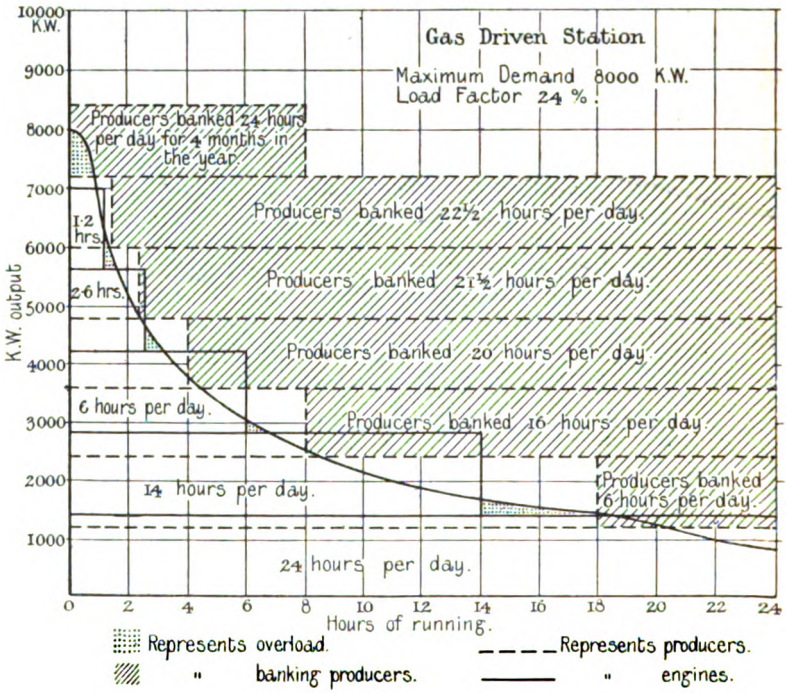

FIG. 12.

The cost of waste and engine-room stores is estimated at 0·002d. per unit generated for both the steam plant and for the gas plant, thus bringing the total cost of oil, waste, and stores to £438 for the steam plant, or 0·005d. per unit, and to £1,345 for the gas plant, or 0·0154d. per unit.*

Water.—Each steam unit requires 288 thousand gallons of cooling water per hour, of which it is estimated 3 per cent. will be evaporated from the cooling towers. The water evaporation will therefore be 8,640 gallons per hour × 12,800 engine-hours ; 110,500 thousand gallons per annum at 6d. per thousand gallons = £2,760 per annum.

* The cost of oil, waste, and stores for the gas-engine plant at the Seraing Works of Messrs John Cockrill & Co. is stated to be 0·013d. per unit generated, the output of this plant being 24,000,000 units per annum (see page 259, Mr. P. R. Allen's paper on the "Construction of Large Gas Engines," before the Manchester Association of Engineers).

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The cooling water required for the gas engines is found to be about 12 gallons per hour per kilowatt output; each 1,500-k.w. plant will therefore require 18,000 gallons per hour.

We have again assumed an evaporation of 3 per cent.

The water evaporated from the engine cooling towers will thus be 540 gallons per engine-hour × 17,450 engine-hours = 9,500 thousand gallons per annum.

The water consumption for the producers is estimated at 35,000 gallons per day = 12,700 thousand gallons per annum.

The total water for the gas plant will therefore be 22,200 thousand gallons at 6d. per 1,000 = £555.

Labour.—The labour charges are calculated upon the assumption that the following staff would be required for the respective schemes :—

STEAM PLANT.

	£	s.	d.
Three charge engineers at £3 per week ...	9	0	0
Three switchboard attendants at 30s. per week	4	10	0
Four drivers at 35s. per week	7	0	0
Four assistant drivers or cleaners at 28s. per week	5	12	0
Three firemen at 35s. per week	5	5	0
* Nine boiler house and auxiliary plant hands at 30s. per week	13	10	0
Three men for unloading coal and removing ashes at 28s. per week ...	4	4	0
	£49	1	0

Total labour charges per annum, £2,550.

GAS PLANT.

	£	s.	d.
Three charge engineers at £3 per week	9	0	0
Three switchboard attendants at 30s. per week	4	10	0
Six drivers at 35s. per week...	10	10	0
Five drivers at 30s. per week	7	10	0
Two cleaners at 28s. per week	2	16	0
Three producer hands at 35s. per week ...	5	5	0
Six producer hands at 28s. per week ...	8	8	0
Seven ammonia recovery hands at 30s. per week	10	10	0
Two men for unloading coal and removing ashes at 28s. per week	2	16	0
	£61	5	0

Total labour charges per annum, £3,180.

* Includes men for cleaning boilers.

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Maintenance and Repairs.—This is the most difficult item to estimate with any degree of accuracy for either the steam or gas plant. It is practically useless citing experience of existing stations, as the conditions in no two are alike. It is, for instance, quite possible to quote cases where, either through faulty design or construction of the plant or from some other cause, gas engines have been a continual source of trouble, and it is equally possible to give numbers of cases where large gas-driven electric generators have been running for years with remarkably low charges for maintenance and repairs.

The same may be said of steam-turbine installations.

The better way to arrive at an approximate conclusion as to what should be allowed for this item is to consider what are the conditions in the respective cases which are liable to lead to trouble.

Taking steam turbines first, the principal risk appears to be that of the blades stripping. Whilst the large number of steam turbines that have now been running for some years without any serious trouble of this nature would appear to indicate that this risk is small, the fact must be faced that cases have occurred, even with turbines erected during the past twelve months, where heavy repair charges have been incurred by loosening and stripping of the turbine blades.

With large gas engines the most serious risk is that of the fracture of the piston or of the cylinder liners. Troubles of this nature, whilst somewhat frequent in some of the earlier large gas engines, owing to makers not having had experience to enable them to so design these parts as to reduce the expansion and contraction under wide ranges of temperature to a minimum are, however, fast disappearing.

As far as the actual wear and tear of the moving parts is concerned, this will probably be smaller in a gas engine than in a steam turbine. Practically the whole of the weight of the pistons and piston rods is carried on heavy side blocks external to the engine cylinder. The wear upon the cylinder liners is, therefore, extremely small, being only that due to the compression of the piston rings against the liners.

It was thought at one time that the wear on the exhaust valves would be considerable, and in the early design of engines it was considered necessary to water cool these valves to prevent overheating of the valve faces. Messrs. Ehrhardt and Sehmer came to the conclusion some two years ago that the water cooling of exhaust valves was an unnecessary complication, and they have now entirely abandoned this practice for all sizes of engines.*

Numbers of examples are recorded of large engines in Continental generating stations that have been running for twelve or eighteen months without being opened out.

The repairs of generators would certainly be lower for a gas-driven plant than for a steam or turbine-driven plant.

* At the recent Manchester Electrical Exhibition an exhaust valve was exhibited that had been taken out of a 2,000–2,200 B.H.P. single-tandem Ehrhardt and Sehmer gas engine which had been running for 466 12-hour shifts. The valve had not been re-ground during this time and appeared to be practically in as good condition as the day when it was put in.

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One of the principal items in the maintenance of a steam station is that of the repairs of steam pipes, whereas the maintenance of pipe-work in connection with a gas station will obviously be extremely small. In the first place, the working pressure is only 1 in. or 2 in. above atmospheric pressure. There is consequently no danger of joints leaking if the pipes are once properly installed. Again, as no steam-pipe lagging is required for the gas pipes an appreciable item of expense in maintaining these is entirely eliminated.

The principal liability of repairs to pipe-work appears to arise from the risk of the exhaust pipes being attacked by sulphuric acid if the water is allowed to mix with the exhaust gases and combine with the small percentage of sulphur in them.

The cost of producer repairs appears to be a very small item, and will undoubtedly be only a fraction of the cost of repairs to high-pressure steam boilers. The Power Gas Corporation estimate that the total cost of repairs to the entire producer plant, including the ammonia recovery appliances, shown in Fig. 4, would not exceed on the average £500 per annum over a period of a number of years.

We are of opinion that the total cost of repairs for the 10,000-k.w. gas-driven station, including engines, generators, producers, all auxiliaries and buildings, would not exceed £4,000 per annum, or 0·046d.* per unit generated.

We have also estimated the repairs and maintenance of the steam plant at the same rate as the gas plant, though we believe that this is a lower figure than has yet been obtained in any steam station over a period of several years.

Antiquation, Depreciation, and Interest.—As the use of large gas engines is so comparatively new in this country, some engineers may be inclined to think that the designs will be so altered during the next few years as to make it necessary to set aside a large amount to provide against antiquation. Those, however, who have visited many of the large gas-engine installations on the Continent will have been impressed by the great similarity in general design between all the engines that have been erected during the past three or four years. Several members of the party who recently visited the very fine gas installation at the Homecourt Iron and Steel Works were particularly impressed by the fact that they saw engines running side by side bearing various dates from 1904 to 1907. These engines appear to be identical in every respect, and they have been maintained in such excellent order that the earlier engines appear to be running in every way as satisfactorily as those of more recent date. The entire absence of vibration in connection with these engines (it has been found possible to balance a penny on edge on the cylinder of a 2,000-H.P. engine running on load) would appear to indicate that in all probability these engines will be running as well twenty years hence as they are to-day.

* Mr. Allen in his paper previously referred to states that the total cost of repairs at the Cockrill Works amounted to 0·023d. per unit.

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The correct amount to allow for interest and depreciation on electric generating machinery is a somewhat debatable point. It is usual in preparing estimates for industrial plants to allow 10 per cent., but Mr. Snell in his paper on "Cost of Electrical Power for Industrial Purposes" justifies the figure of 6¼ per cent.

As this point has a very important bearing on the comparison of steam and gas engine cost, we have in each case shown the comparative cost including these charges at 10 per cent. and alternatively at 6¼ per cent.

The total running costs of generating 21,000,000 units under the above conditions will, we estimate, be respectively as follows:—

	Gas.			Steam.		
	£	s.	d.	£	s.	d.
Total cost of coal at 12s. per ton	12,280	0	0	19,968	0	0
Less sale of sulphate of ammonia	5,376	0	0			
Net cost of coal	6,904	0	0	19,968	0	0
Oil, waste, and stores... ...	1,345	0	0	438	0	0
Water	555	0	0	2,550	0	0
Labour	3,180	0	0	2,590	0	0
Repairs	4,000	0	0	4,000	0	0
Interest and depreciation at 10 per cent. on capital ...	17,687	0	0	13,952	0	0
Total cost	£33,671	0	0	£43,498	0	0
Total cost per unit	0·385d.			0·477d.		
Total cost, allowing 6¼ per cent. for interest and depreciation	£27,040	0	0	£38,266	0	0
Total cost per unit	0·308d.			0·437d.		

The total cost (including 6¼ per cent. for interest and depreciation) of generating power by steam = 42 per cent. greater than the cost of generating power by gas.

Effect of Price of Coal and Load Factor.—In the particular case we have considered the conditions are more favourable to the use of gas engines than in many of the existing provincial municipal electric supply schemes in this country. There are at present only 15 public electric supply undertakings working at a load factor of over 24 per cent., though many more have load factors varying from 20 to 24 per cent. In many cases, too, a suitable coal can be obtained at less than 12s. per ton delivered at the works. We will therefore go to the opposite extreme, and consider the case of a generating station having the very poor load factor of 10 per cent., and able to obtain fuel at 8s. per ton. We will also assume that the maximum output is only 4,000 k.w., and

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that the use of sulphate of ammonia recovery plant for a portion of the producer plant as in the scheme previously considered is not justifiable. Under these conditions the saving in fuel effected by using gas engines is little more than sufficient to pay the 10 per cent. interest and depreciation charges on the higher capital outlay of the gas plant.

It has been suggested that for such conditions a combined gas and steam plant might be used, the gas plant being utilised for the long-hour portion of the load curve and the steam plant with its lower capital charges for the peak load.

The following table shows the estimated annual running costs with plants consisting respectively of—

A. Five 1,000-k.w. steam turbo-generators.
B. Seven 700-k.w. gas engines and generators.
C. Four 1,000-k.w. steam turbo-generators and two 700-k.w. gas engines.

Running cost, 4,000-k.w. plant; 10 per cent. load factor.
Distribution efficiency, 80 per cent.
Units generated, 43,800,000.
Coal, 8s. per ton.

TABLE I.

	A. Steam.	B. Gas.	C. Combined.
	£	£	£
Coal	3,916	2,073	2,791
Oil and waste	95	297	248
Water	710	100	170
Labour	2,400	2,500	2,745
Repairs	1,250	1,250	1,250
Interest and depreciation at 10 per cent.	7,452	9,578	8,639
	£15,823	£15,798	£15,843
Cost per unit generated ...	0·867d.	0·866d.	0·868d.
Total cost, including interest and depreciation at 6¼ per cent.	£13,037	£12,209	£12,608

It appears, therefore, that for the above conditions and a 10 per cent. charge for interest and depreciation, there is nothing to choose between the different types of plant as far as running cost is concerned,

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but with interest and sinking fund charges of 6¼ per cent. the combined station shows an overall economy of 3 per cent. over that of the steam plant and the all-gas plant an improved economy of 6 per cent. over the all-steam plant.

We have calculated on the same basis as above the total running costs per unit generated, with coal at various prices, ranging from 2s. 6d. to 15s. per ton, and with load factors of 10, 15, and 24 per cent. The resulting curves are shown in Figs. 13 and 14 respectively

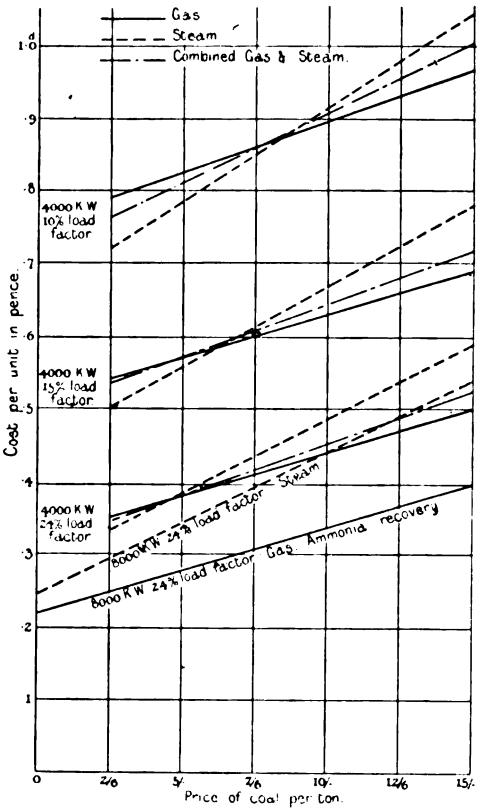

FIG. 13.

—the former including 10 per cent. capital charges and the latter corresponding charges of 6¼ per cent.

It will be seen that under no condition is it worth while, when putting down a new station, to instal a combination of steam and gas plant. With non-recovery plant and coal above a certain price, gas plant is more economical, and below that price, steam plant alone is more economical than either gas plant alone or combined steam and gas.

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These remarks apply only to entirely new installations. There are, however, many existing installations equipped with comparatively inefficient plant, where a large economy would be effected by installing one or more gas engines, which would be used for the flat portion of the curve, the inefficient plant being retained for the peak load and standby.

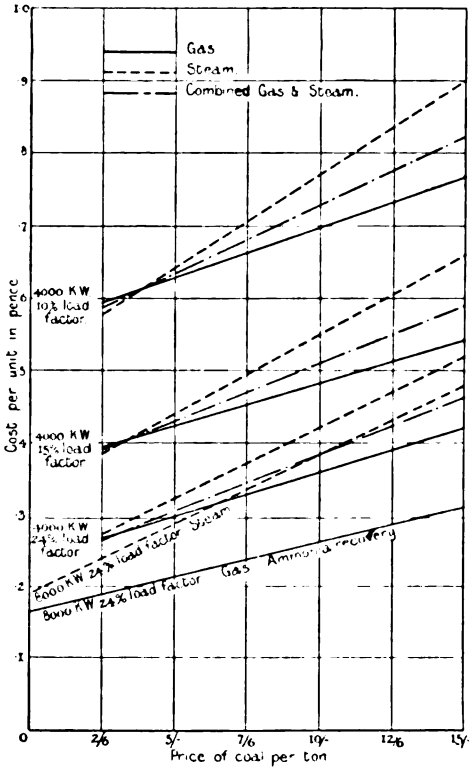

FIG. 14.

It will also be seen that if the size of the installation or the load factor permits of recovery plant being used, gas plant is more economical than steam plant however low the price of coal.*

* In an article which appeared in *Electrical Engineering*, October 24, 1907, and other papers, one of the authors expressed the opinion that with coal at 10s. per ton steam turbines would prove more economical than gas engines for load factors below 30 per cent., and suggested that in certain cases a combined steam turbine and gas plant would prove more economical than either steam plant alone or gas plant alone It was, however, then assumed that the total capital cost of an entire gas installation would be 43 per cent. higher than that of a steam-engine installation. On obtaining closer quotations for both steam and gas plants, it now appears that the capital cost of the latter should not exceed that of steam turbine plant by more than 27 per cent., and the difference is, therefore, insufficient to justify any attempt to reduce the total capital charges by installing steam turbines to deal with the peak load.

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No attempt has been made in the foregoing paper to deal with the question of gas engine and producer design, as so many excellent papers have been written on this subject, notably :—

1. Mr. Humphey's paper before the Institute of Civil Engineers.
2. Mr. Rheinhardt's paper before the Iron and Steel Institute.
3. Mr. P. R. Allen's paper before the Manchester Association of Engineers.

On the other hand, we believe that the question of the economics of the use of large gas engines for generating electric power has not previously been dealt with.

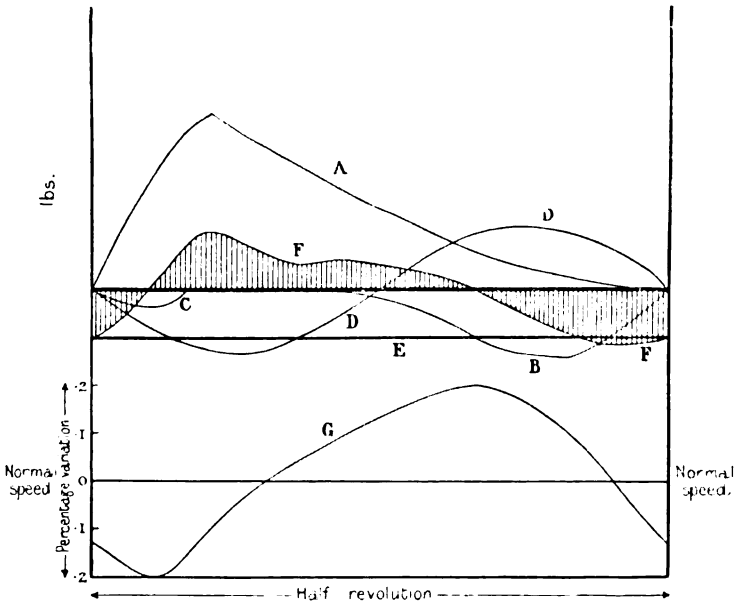

FIG. 15.

We wish to take this opportunity of thanking the many friends, too numerous to mention individually, who have furnished us with particulars of both capital and running costs, and other information relating to both steam and gas plants, on which the estimates in the paper have been based.

APPENDIX A.

The basis on which the cyclic irregularity curves, illustrated in Fig. 6, are constructed, is illustrated in Fig. 15; these particular curves being for a double-acting single-tandem engine.

The size of unit taken is 750 B.H.P. for all types of engine.

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Curve A represents the positive pressure in lbs. upon the crank pin due to the expansion of the gases throughout the explosion stroke. As the results are merely comparative, the connecting rod is assumed to be of infinite length in each case. B shows the negative pressure due to compressing the gases on the compression stroke. C is the back-pressure prior to opening the exhaust valve. D shows the negative and positive pressures due to the inertia of the moving parts. E shows the negative pressure resulting from the external load or useful work of 750 B.H.P. plus the engine friction. F is the resultant fluctuation of crank effort curve—the shaded area enclosed by this curve above the zero line represents the energy put into the flywheel, and the shaded area below the line represents the energy given out by the flywheel. The areas above and below the line obviously cancel out. G is the variation of angular velocity throughout the entire stroke. In the case of double-acting single or twin tandem engines the curves will be similar for every stroke, but for single-acting tandem or double-acting single-cylinder engines this will not be so.

G is deduced from F by the following formula :—

$$\text{Fluctuation of energy} = \frac{I}{g} q w_0^2.$$

Where w_0 = normal angular velocity.
q = percentage fluctuation of speed allowed.
I = moment of inertia of the flywheel.

APPENDIX B.

Brief particulars are given below of three gas-driven electric traction plants.

1. JAMESTOWN AND WARREN STREET RAILWAY, U.S.A.

(This plant has been running since December, 1905.)

Load.

Four 35-ton inter-urban cars, mileage 800 per diem.
A number of street cars, mileage 2,381 per diem.
Total ton-miles = 58,110 per diem.

Power House Equipment.

Two 500-B.H.P. Westinghouse horizontal tandem engines.
Two 300-k.w. Westinghouse 25-cycle alternators, 150 revs. per minute.
Reserve plant: Three 275-H.P. vertical Struthers Wells, with belt-driven generators.

Gas Consumption.

Natural gas, heat value approximately 1,000 B.Th.U.
Gas consumption per car-mile = 26 cub. ft.
Gas consumption per ton-mile = 1·46 cub. ft.

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Oil Consumption.

0·000253 gallons (cylinder) per B.H.P.-hour.
0·000345 gallons (engine) per B.H.P.-hour.

Cooling Water.

5·65 gallons per B.H.P.-hour.

The operating staff consists of four men and one chief engineer, the plant being in operation about twenty hours a day.

During the six months preceding our visit the reserve plant had not been in requisition, except to take overloads due to snow.

We understand that the repairs for the nine months preceding were :—

Labour, staff only.
Material, under £2.

The variation in load is very considerable.

At the time of our visit the following readings were taken at one-minute intervals :—

Volts.	Amperes.
362·0	500
363·0	200
358·0	1,350
360·0	700
359·5	1,000

These engines are running perfectly in parallel.

They are synchronised by the ordinary lamp method, and we are informed that the entire operation of unloading, synchronising, and loading again has been repeatedly performed in 25 seconds.

No hunting is observable on excessive loads.

It is admitted that misfires occasionally occur, but no instance of electrical trouble due to this has occurred.*

2. Milwaukee Northern Railway, U.S.A.

(Plant started October, 1907.)

Load.

Inter-urban cars to carry 52 passengers at average speed of 25 miles per hour, and street cars.

Load varies from half-load to 50 per cent. above full load.

Hours of running : 19 to 20 hours per day.

Power House Equipment.

Three Allis-Chalmers twin-tandem 1,500-H.P. engines, coupled to 25-cycle 1,000-k.w. alternators.

(The engines are capable of developing a maximum of 2,000 B.H.P.)

4,000-H.P. down-draught Loomis Pettibone gas producers, with a 25 per cent. overload capacity for 5 hours.

* We are indebted for some of the above figures to Mr. Bibbin's paper read before the Engineers' Society of Western Pennsylvania.

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Fuel used is slack of 11,500 B.Th.U.
Gas formed has 125 B.Th.U. heat value.
At the time of our visit the fuel consumption had not been authenticated.
Oil Consumption per Day.—Journal, oil filter system; cylinder, 8 gallons per engine.
The plant had been running for six months without a hitch.

The following remarks, sent by the Company to the Gas Engine Committee of the National Electric Light Association, are characteristic :—

Continuity of Service.—"Absolutely O.K."
Reliability.—"Absolutely O.K."

3. Boston Elevated Railway, U.S.A.

(Plant started May, 1906.)

Load.—Street cars.
*Power House Equipment.**
Two 600-B.H.P. American Crossley engines.
Two 350-k.w. direct-current generators.
One pair of Loomis Pettibone gas producers using soft coal.

TABLE II.

Particulars of Fuel Consumption, taken over Seven Months, 1907.

	Kilowatt-hours Generated.	Total Lbs. Coal, including Coke.	Coal per Kilowatt-hour.	Engine Load Factor.
			Lbs.	Per Cent.
January...	204,080	391,223	1,917	84·2
February.	175,200	364,817	2,081	86·0
March ...	192,250	405,050	2,120	87·4
April ...	202,870	401,150	1,975	82·3
May ...	118,640	234,705	1,979	78·3
June ...	35,770	90,991	2,542	73·3
July ...	60,170	124,452	2,065	82·8
Total...	988,980	2,012,388	Average 2,034	Average 83·3

Water for all Purposes.—28 gallons per k.w.-hr., obtained free of cost.
Oil.—0·000255 gallons (cylinder), 0·001 gallons (engine), per k.w.-hr.
Labour.—Eleven men, divided between two shifts of 8 hours each.

* A further installation has been lately put down, driven by two De La Vergne Korting engines of similar capacity.

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Comments of the Company sent to the National Electric Light Association Committee :—

Reliability.—" Plant has proved absolutely reliable."
Economy.—" Makes saving of 41·5 per cent. in coal over steam."
Troubles.
" Very few, practically none that affect operation."
" Back-fire and pre-ignition practically eliminated."
Continuity of Service.
" Has carried good loads and will continue to do so, if time given to clean producers."
" Require considerably more time for inspection, etc., than would similar size steam engine."

German Gas-driven Installations.

The waste gases from a large number of blast furnaces in the Westphalia district have, for some years, been utilised for generating electric power for use in the iron and steel works and other industrial works in the neighbourhood.

The output from one particular combination of this nature exceeds 50,000,000 electric units per annum. A portion of this total output is generated by steam-driven generators and the remainder by gas-driven generators, the respective plants being located in different works and under entirely separate supervision.

A keen competition has always existed between the engineers in charge of the respective plants, there being a natural desire on the part of each to show the lowest total cost.

A few months ago, a committee, consisting of steam and gas experts, was appointed to closely investigate the total cost of generating power under the respective systems.

The steam plant tested consisted of one 8,250-H.P. (5,500-k.w.) turbo 3-phase alternator, and the gas plant of four 2,000-H.P. single-tandem gas engines directly coupled to 3-phase alternators.

Each installation was debited with a charge of 10 per cent. on the total capital outlay involved to cover depreciation, in addition to interest charges. These extremely liberal fixed charges would obviously tend to favour the steam plant with its lower capital charges.

The actual cost of labour, stores, and repairs was taken over a period of eighteen months.

As the waste gases available were insufficient for the total power required, it was necessary to provide coal for the balance, and the value of the gas was therefore in each case taken as being equivalent to the cost of coal having a corresponding useful heating value.

The calorific value of the coal used was 11,800 B.Th.U. per lb., and cost 11s. per ton delivered in works.

All instruments used for the tests were carefully calibrated, and every precaution was taken to ensure accurate results.

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(*j*) Price per Ton.	(*k*) Ratio of Current Generated by Turbines to Total.	(*l*) Fuel per Unit Generated.	(*m*) Overall Thermo-Dynamic Efficiency.
	Per Cent.	Lbs.	Per Cent.
8/6½	nil	4·770	5·38
7/11½	2·4	4·460	7·30
7/11½	nil	4·080	7·95
13/3	nil	5·400	5·28
10/13⅜	nil	3·220	8·18
9/9½	nil	3·060	9·30
9/6 & 10/6	nil	7·000	3·90
—	17·7	5·700	5·45
6/8	100·0	3·700	7·63
6/8	*nil*	9·070	3·70
8/8	88·0	3·200	8·30
10/5·78	67·0	4·770	6·50
11/3½	100·0	4·020	6·78
11·7½	25·0	3·770	6·75
10/9½	—	3·180	7·95
14/4	100·0	4·800	5·64
10/-	10·0	4·640	5·65
9/6 to 10/-	85·0	4·075	7·60
8/3 to 10/3	89·0	5·410	5·25
14/10½	—	4·680	6·49
12/6½	nil	4·060	7·30
8/9	100·0	3·680	6·78
11/- to 14/5	—	3·100	9·05
fficiency of above twenty replies =			6·83
am Electric Stations at			3·5 to 4·5

—	—	2·038	15·00
(2d. per) (1,000)	—	—	12·40
—	—	1·840	12·85
10/-	—	2·125	13·90
16/-	—	1·950	14·10
—	—	2·000	13·75
—	—	1·800	14·60
9/-	—	2·064	15·05
efficiency of above eight replies =			13·95

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The boilers for the steam plant were coal fired, and the coal used was carefully measured day by day for a period of one month.

The gas consumption for the gas plant was measured by alternately filling and emptying the gasometers. The gas consumption tests were also continued over one month under all conditions of load.

The average load factor throughout the test was 65 per cent.

The Committee finally reported that they found the total cost, including all capital charges, of generating power by gas plant, under the above conditions, was 2·12 pfennigs (= 0·25d.) per unit, and by steam turbines 3·3 pfennigs (= 0·39d.) per unit—the cost of generating by steam being 56 per cent. greater than by gas.

In view of this report the Board—whose only interest is to supply the greatest output at the lowest cost—have resolved to instal additional gas-driven generators, having an aggregate output of 35,000 H.P.

We understand that a considerable portion of the above output is sold to a public electricity supply distributing company at 3·5 pfennigs (= 0·42d.) per unit.

Notes on Table III.

(*a*) Inquiries were sent to all public electric supply undertakings in this country having an output exceeding 7½ million units per annum. It was requested that in cases of undertakings having two or more stations running in parallel, results from the most modern and efficient plant should alone be given. Replies from (14) and (14A) are examples of results from both the modern and efficient station and from the old and comparatively inefficient station of one undertaking. The (14A) results are not included in the mean result.

(*c*) The units generated are the total units supplied to the feeders. Current used for driving auxiliary plant in generating station, works, lighting, etc., is not included under this heading.

(*e*) The load factor is calculated from—

$$\frac{\text{units supplied to feeders} \times 100}{\text{maximum load on feeders} \times 8{,}760}.$$

(*f*) The plant factor is calculated from—

$$\frac{\text{units supplied to feeders} \times 100}{\text{plant hours run} \times \text{capacity of plants}}.$$

(*g*) The fuel consumption is the total fuel used for all purposes.

(*h*) The calorific value of the fuel is the engineer's estimate of the mean calorific value based on periodic calorimeter tests.

(*k*) The inquiry respecting the ratio of current generated by turbines was originally inserted with a view to ascertaining what portion of the total current was generated by modern plant. It is somewhat surprising to find that many of the best results are shown by stations having little or no steam turbine plant.

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(*m*) The overall thermo-dynamic efficiency expresses the ratio of heat units in busbars to heat units in coal pile, or—

$$\frac{3412{\cdot}66 \times 100}{\text{lbs. of coal per unit} \times \text{calorific value}}.$$

It is interesting to note that there is considerably less variation in the gas plant results than in the steam plant results, the latter varying between 3·96 per cent. and 9·3 per cent., a difference of 135 per cent. on the lower figure. The gas efficiencies, on the other hand, range from 12·4 per cent. to 15 per cent., a difference of only 21 per cent. on the lower figure. It is somewhat surprising that the difference should be so small when the very large difference in the output of the plants and the large difference in the load factors is taken into consideration.

These results would appear to confirm statements that have been made to the effect that the gas consumption per unit generated is practically constant for any size of plant—that the standby losses are less, and the discrepancy factor considerably smaller and more constant than that of steam plants.

Discussion.

Mr. Woodhouse.

Mr. W. B. Woodhouse: I am sure we have all listened to the authors' paper with a very great deal of interest. It is the most determined attack that has been made on steam plant, and they have put an extremely strong case before us. During the last week I have had the pleasure of reading the paper, and I have gone into a great many points and compared them with the figures that one gets with steam plants, and I must say that, as the authors put it, it almost convinces one. But there are some few drawbacks, and I should like to say a few words about them. It seems to me that the whole question divides itself practically under five headings. First of all, what is the most efficient plant? I do not think any one will discuss that point; we are all agreed that a gas engine is the right thing from the point of view of thermal efficiency, and we are all extremely sorry that we are wasting the nation's coal on steam engines. The next point is, which is lower in the first cost? I take it we are all agreed on that point. The third point is, which is the lower in running costs apart from fuel? The authors in their comparison make the two about equal. That will bear considerable discussion. The fourth point, which is as vital a point to the supply undertaking as anything else, is, which is the more reliable? Finally, in any particular case, one must consider, which is the proper type of plant to put in? Take the first point with regard to efficiency. They have given a comparison in Table III. of the results from a number of English stations, but those stations do not, as a matter of fact, include the station I am connected with; and my neighbour, Mr. Gripper, tells me that there is another power station also missed out. As these two stations have got modern steam plant, I know the figures would have shown a very favourable

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Mr. Woodhouse.

comparison with any of the steam figures given in Table III. With regard to the gas-plant efficiencies, one notices there is a case with a load factor of 90 per cent., which, of course, none of the steam stations has. I do not think that the authors want us to take that table too seriously, but they want us to take the figures of the comparative coal consumption given in the body of the paper—namely, 3·5 lbs. for steam as against 2·18 for gas. I will take those figures, but I do not know that I am prepared to agree to take 12s. a ton for coal, neither am I prepared to agree that where we are paying 12s. a ton for coal for a producer, that we are necessarily going to pay it for a steam plant. The authors have not said a word about producers; they have avoided the subject, except a general description of a bituminous producer. I think the by-product bituminous producer has been on the market for twenty years. We heard almost as much of it, if not more of it, ten years ago than we do to-day, but we know from people who are using them that they are extremely difficult things to operate, and that the class of coal used has to be chosen very carefully. A soft, tarry coal will give a lot of trouble. A coal with a low percentage of nitrogen is of no use for the by-products; the caking coals, such as are mined in Durham and Yorkshire, are unsuitable; that is to say, a special class of coal must be bought for the producer, but any coal on the market of the same thermal value can be used with steam boilers. Therefore it is fair in making the comparison to take the cost of coal for steam raising at a lower price than for the producer. The figure depends on the district. The next point in the costs is that of water; the figure of £2,550 a year is given as the cost of water for the steam plant. It seems to me, with all due respect to the authors, that the engineer who put the typical station down in that place was not doing the right thing. If the value of the water is capitalised at ten years' purchase, and the cost of the cooling towers is added, the capital value of that water supply is £32,400, which, in this well-watered country, would buy several suitable sites in most of the industrial parts of England. Admittedly in several cases where one is tied down to an iron works, or a colliery, or the location has been fixed for other reasons, cooling towers may be necessary, but in taking a general case, I think we may fairly wipe that particular item of water out from both the bills of costs. I say wipe it out altogether, but perhaps I should not say quite. I believe in a town one may come in conflict with the local authority on the subject of ammoniacal water; I do not know whether it is necessary to put down plant to treat that.

The by-product producer, the Mond type of producer, costs a great deal more and is a great deal more complicated than the non-recovery producer, but whichever type one uses the important point is not so much making gas as making clean gas. You have to put down scrubbers and washers and apparatus of all kinds to clean your gas from dust and from tar. One of the biggest difficulties, I take it, with the gas engine is the question of getting clean gas. If you use a soft

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Mr. Woodhouse.

coal with a high percentage of volatiles you get a quantity of tar into the cylinders, and you will have your cylinders going very rapidly. If you get dust or dirt through the cylinders and valves they will also go rapidly. So that we have to consider, in operating a gas plant, not only the producer, which is a comparatively simple thing, but all the auxiliaries, pumps and scrubbers, and filtering devices of all kinds. All those things have to be operated; they all use power, and they occasion a considerable expenditure. I must disagree with the authors' estimate of boiler standby losses. We know well that a steam boiler will probably have as high an efficiency at half load as it has at full load. And boilers not only need not be banked to the extent suggested, but may be forced when required. On the other hand, a producer will not stand forcing if one wishes to obtain a fair yield of ammonia. The point of capital cost arises in connection with the question of the size of units. The authors take a station of 8,000 k.w. Doubtless that is a fair-size station, but it is obvious that had they taken a station of 20,000 k.w., or even one of double the figure they have given, 16,000 k.w. instead of 8,000 k.w., then the comparison would have been more favourable to steam turbines. The limiting size of a gas engine depends on the amount of power that can be put on to one crank, or rather it depends on the maximum diameter that you can give your cylinder. On a small scale, any one that uses motor-cars knows that with cylinders above 4 in. troubles begin above a certain size cylinder with a gas engine, and for the reason that the volume goes up as the square of the diameter and the cooling surface only as the first power of the diameter, there is trouble. The authors tell us that practically 1,000 H.P. per cylinder is the limit. I think it is quite the limit. We are recommended to put in engines of 1,800-k.w. capacity. We may take it that the authors consider that is the largest size they would venture to put in, as it is the one they are putting forward, but it is not the largest size of turbine. If the size of the station is doubled the number of gas sets is doubled, and the capital expenditure is doubled. If a turbine station is doubled the capital expenditure will not be increased by more than 50 or 60 per cent., and that alters the comparison considerably. The authors seem to me to be rather fond of small units. They suggest a lot of little gas engines and producers, and in the steam stations a lot of little turbines and boilers of 10,000 lbs. evaporative capacity. I do not think that one would put in a boiler of that size. There are 20 boilers recommended in this particular station, whereas one would put in 7 boilers of 30,000 lbs. evaporative capacity, and would buy them for very much less than the authors could buy their little boilers. I do not think it is quite fair to suggest that the average engineer would put in an economiser to each boiler—20 little economisers and 20 little boilers, and so on. The station would become extremely expensive to run, and, worse than that, it would be a very sad waste of capital. Finally, with regard to the point of total costs, I do not agree that the authors should include such a big charge for water in the running expenses; I do not

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Mr. Woodhouse.

think the cooling towers should be necessary, and I would reduce their estimated capital charges on the steam plant very considerably. I have done that, and have made a comparison on the particular load factor chosen. Taking that particular load factor, and taking that particular size station, I reduce the gas charges to 0·47 and the steam charges to 0·456d. per unit. I have only time to say one thing about this estimate: I disagree with their figures for repairs, and I have taken the liberty of assuming that the repairs on a gas plant will be just double those on a steam plant.

Communicated: The estimate of capital cost of the steam plant I consider should be reduced to £105,000 by the omission of cooling towers, by lessened cost per kilowatt of turbines of larger size, and by a reduction in the cost of buildings. I consider that 10 per cent. is too little to allow for interest and depreciation, and have taken 12 per cent. It is a sound commercial principle not to invest capital in a type of machine that only possesses advantages when earning a low rate of interest if there exists another type on which the net earnings represent a higher rate at the same total costs. I estimate the total running costs as :—

	Costs in Pence per Unit.	
	Gas.	Steam.
Fuel, net cost	0·079	0·228
Repairs	0·100	0·050
Wages and Stores	0·051	0·034
Interest, etc., at 12 per cent.	0·240	0·144
Total	0·470	0·456

Or, to put this result in another form, if the net return on the capital expended is, in the case of the gas plant, 12 per cent., the return on the capital expended on steam plant will be over 13 per cent.

It may be pointed out that the advantage of the gas station's efficiency increases with a higher load factor, but, on the other hand, if we considered a larger station the steam costs would be reduced in every part. Assuming, however, that the authors' claim for reliability of gas engines is a just one, there is very little between the costs of the two types of plant, and large gas engines in the future must merit our most serious consideration. I do not think that the last word has been said in modern boiler-house practice, and I would be interested to have the authors' views on a combination of producers, gas-fired boilers, and steam turbines.

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Mr. Chattock.

Mr. R. A. CHATTOCK: The subject of gas engines is particularly interesting to me just now, as I am at present engaged in drawing up a scheme for a big extension in the city I represent. I naturally have to look at all sides of the question, and I am getting figures for gas performances and comparing them with figures for steam. I think the authors have placed the subject very fairly before us. Several of their figures, as the last speaker has pointed out, are open to criticism, but I think the authors have done their best to make out a very good case for the gas engine. There is one point in connection with the over-load capacity of these gas engines and generators which the authors mention, and to which I should like to draw attention, namely, they say that a 10 per cent. overload can be obtained from the gas engines, and they compare that with a 33 per cent. overload for the steam plant. I think neither of those figures is suitable for the electrical side of the equipment—that is, the generator—because an electrical generator as generally installed now is reckoned to have an overload capacity of about 25 per cent. for a period of 2 hours, and that figure is governed by the temperature rise of the machine more than by anything else. If we only allow a 10 per cent. overload capacity we are wasting the capacity of the generators to the extent of 15 per cent., while I think a 33 per cent. overload capacity would mean that generators considerably larger than is necessary would have to be put in. An overload of 25 per cent. is usual. The authors give an estimate of the repairs necessary on these gas engines and producers, which it is very difficult for us steam engineers to criticise. We can only take that figure, and endeavour to find out if it is accurate in the best way we can. It seems to me that the figures given in comparison with the repairs to a steam plant are certainly on the light side. I should anticipate that the repairs on gas engines, with their much heavier internal strains and possibly greater wear and tear on the parts, would be greater. With regard to the figures for the producer plant, I take it that the repairs are all included in the figures given by the authors, but they do not definitely say that is so. As regards the capital cost of the plant, I understand that the cost of the gas engines is considerably heavier than the cost of the steam engines and turbines. Comparing the gas engine with an ordinary reciprocating steam engine, I cannot see why the cost should be so much higher. The parts of the gas engine are quite simple. Of course they are very heavy, because they have to stand much heavier initial strain, but looking at it as an engine I cannot see where the great extra cost should be necessary, and I can only anticipate that when the engines come more into general use, if they ever do so, the cost will go down approximately to the same level as the reciprocating steam engine. As regards the water consumption on the steam plant, I agree with the last speaker that the figure given is very high; but in looking through the paper I notice that even that figure only includes the water that is lost in evaporation in the cooling towers. No mention is made of make-up water required in the boilers. I should like to

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know if that is an oversight, or whether the make-up water in the boilers is meant to be included in the figure given for water evaporated in the cooling towers. The thermal efficiency of the gas engine plant is certainly very much better than that of the steam plant. I have noticed, however, that in the average figure given of 6·73 per cent. for all the steam stations, it is simply an arithmetical average of the figures in the last column. Many of those figures refer to stations in which the output is very much heavier than in the case of others, and I think it is only fair that the figures relating to the stations with heavier outputs should have more preponderance in that average in order to get a more accurate and comparative figure for the thermal efficiency. I recently had an opportunity of inspecting several of these large gas-engine stations at work on the Continent, and I was very much struck with the quiet running of the engines, their simplicity, and the ease with which they were handled. There is no doubt that those engines are perfectly satisfactory for parallel running with alternators. I saw on one system alone one station connected up with several others, up to a total capacity of about 50,000 H.P., running on one large network of high-tension cables. Some of these stations were steam and some were gas driven, and there seemed to be absolutely no trouble in running the engines together and giving a satisfactory supply. I also had an opportunity of examining one of the engines that had been in use for some years—I think about three years. It had been taken to pieces, and I had an opportunity of seeing the inside of the cylinders, the pistons, and the valves. They all appeared to be in perfect condition, and there did not seem to be any extraordinary wear about them; in fact, not so much as in many steam engines. I think, considering that point, there is no doubt that the repairs of these engines should not be so very much heavier than the steam engines. Where I think it probable that the repairs will come out heavier will be in the producer plant. Mr. Chattock.

Mr. E. J. Fox: In the first place, with regard to capital cost the units suggested by the authors do not show the turbine up to its best advantage. To get the best results out of steam turbines, I think it is agreed by those who have had experience with their running that we require to do two things: first, we require to "drive" the turbine as much as possible, and make use of it even over varying loads, that is, run it for 24 hours a day, 6 days a week, if there are facilities for doing so; and, secondly, that we must take advantage of the heavy overload capacity of which the turbine is capable, even to the extent of coupling to it an alternator capable of running between 50 and 100 per cent. overload continuously if necessary. I know the suggestion seems ridiculous at first sight, but at the same time it is the right thing to do. Take the case of Mr. Dickinson's station at Leeds; he has installed two turbines primarily on the ground of capital cost. At the time his extensions were decided upon, there was practically no difference in steam consumption between the turbines offered and reciprocating engines already installed. On test there is scarcely any Mr. Fox.

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Mr. Fox.

difference between the two forms of prime mover, and yet the actual difference on running is represented by 200 tons of coal a week in favour of the turbines. Figures cannot account for that; as I have said, the guarantees are nominally the same. The turbine is, however, very much more flexible for meeting the varying conditions imposed by a lighting load, with the result in steam economy indicated above. A very similar result, though not quite so pronounced, has been obtained by Mr. Seabrook, at West Ham. The coal in that installation has come down practically 2 lbs. per Board of Trade unit sold during the last two years. It is not right to credit this economy solely to the economy of the turbine, but it is doubtless due to the greater flexibility with which the turbine adapts itself to the conditions, that is to say, will deal with the smallest and heaviest loads without the necessity of starting up further sets. For these reasons I should say that to deal with an output of 21 million units a year as proposed by the authors, five sets of 2,000 k.w. are more than necessary. For instance, at West Ham one set of this size generated during last year over 9 million units. I suggest for meeting the authors' requirements, four sets of 2,500 k.w. each, with alternators capable of giving an overload of 50 to 60 per cent. continuously if necessary. The extra capital cost for obtaining the heavy overloads is negligible; the turbine costs no more, as the overloads are obtained on pass-valves; the condensing plant costs no more for the reason that its size is proportioned to give the best results at the normal load; at overloads the vacuum is allowed to fall; the alternator costs a little more, but negligible, when the increase is considered, on the price of the complete unit. In this way the £139,000 capital cost given by the authors is reduced to about £100,000 capital cost, and this is, I think, comparable with the £176,000 given for the gas plant. In comparing a steam-turbine and a gas-engine plant, the determining factor is largely capital cost, and consequently the relative capital outlay for steam-turbine and gas-engine plant requires carefully analysing, and it seems to me the figures given in the authors' paper cannot be accepted without correction.

With regard to the working costs, I will not quarrel with the figures given for coal consumption, for the reason that it is the one point on which the gas engine has advantages; the comparative figures given for the item of "labour" for running steam and gas plant require modification. If we deduct the cost of labour set aside in the case of the gas plant for working the auxiliary plant, *i.e.*, the ammonia recovery plant, the actual cost of labour in the gas plant is given as within a few shillings of the cost of labour for the steam-turbine plant. It is inconceivable that the labour for running seven gas engines would be at all as small as the labour required for running four or, to accept the authors' proposal, five turbines. With regard to the cost of repairs, I do not think the authors can mean it seriously when they suggest that the gas-engine repairs are nearly as light as those for steam turbines.

I know that a good deal is said about the maintenance cost of

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turbines being in excess of the cost of repairs of certain other forms of prime mover, but such statements are made at hazard, and I would like to give you some figures in this direction, based on facts. Taking an output of 200,000 H.P. of turbines at work, and spread over a period of four years, the actual cost of maintenance and repairs for the turbine plant, that is for the turbines, alternators, and the condensing plants based on the normal rating of the plant, has been considerably less than 1s. per kilowatt per year. As a matter of fact, the actual cost of the repairs from the time that the plant has been set to work—over a period of four years—has been less than 6d. per kilowatt per year. These figures represent the cost of repairs for the complete output of one firm, and consequently include the rough with the smooth, and give a true average. Isolated cases are useless for a comparison of this description. In the case of the authors' station of 10,000 k.w., this would mean an annual bill for repairs of £500 on the 1s. basis, and £250 on the 6d. basis. I think, therefore, the £4,000 given as representing the cost of repairs for a steam turbine station is very excessive. Mr. Fox.

The only other point I will mention is the question of interest and depreciation on the capital outlay. Ten per cent. is put forward by the authors as adequate, but surely it cannot be argued, taking 5 per cent. as interest on capital, that 5 per cent. is sufficient to cover depreciation on gas engines or steam turbines. In other words, if we were spending our own money, would we not consider that provision should be made to enable us to discard the plant after a period of, say, 10 years? Surely we would not expect either steam turbines or gas engines installed to-day to be sufficiently up-to-date for our purposes in 20 years' time? I certainly think, particularly in the case of gas engines, that a depreciation of 5 per cent. is a very inadequate figure, and that it should be raised to 10 per cent., both for turbines and gas engines. It is probably one of the worst features of municipal trading in this country that the majority of our undertakings are filled with plant at the present time which is useless for commercial purposes, but which is still standing on the books at fabulous sums; in other words, it has never been adequately written off. I think in making a comparison between steam turbines, which is a prime mover essentially of cheap capital cost, and gas engines, a prime mover of essentially high capital cost, that this question of depreciation or "antiquation" should be considered on a proper businesslike basis, and if this is done the gas-engine scheme falls to the ground.

Only one remark more. I think the most eloquent testimony against the adoption of large gas engines is the point that my friend Mr. Andrews has brought out, namely, that a small gas engine will work as economically as a large gas engine.

Mr. P. R. ALLEN: The authors are much to be congratulated on having presented in a most impartial manner the relative merits of gas engines and steam turbines under the conditions that would probably be met with at the present day in a fair-sized central station, and it is very obvious that the preparation of the paper must have been a very Mr. Allen.

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Mr. Allen.

laborious business. From a purely technical point of view the paper calls for little comment, as the proposed lay-outs of both the steam and gas-driven stations are on the latest lines, and are such as would no doubt be adopted by engineers familiar with the latest practice. It will be observed that in the gas-driven station the producer plant is adjacent to the power house. Where the ground available renders this possible this is no doubt desirable, but as in a gas-driven station there is no loss from condensation in the main steam pipes, the producer plant can be placed any reasonable distance away without appreciable transmission losses, and it may be often a convenience to be able to put the producer plant on one side of a railway or canal and the power house on the other. The authors propose to make one-half of the producer plant work with recovery, and the other half without. This proposition has been several times put forward by the Power Gas Corporation, but it is by no means certain that it would not pay to put in rather larger producers with the recovery plant all through, and to sacrifice a little ammonia during the periods the producers have to be overloaded. On a Mond plant the calorific value of the gas, with recovery and without recovery, will be with recovery about 140–145 B.Th.U. per cubic foot lower value, and from 150–165 B.Th.U. without recovery. An 11 ft. 6 in. Mond producer will, working continuously, comfortably gasify 1 ton of slack per hour with a sulphate yield of at least 95 lbs. per ton of fuel, if the coal originally contained 1·3 per cent. nitrogen, so that if the producer were worked at its best load continuously it would give 1 ton of sulphate per day, and if the exigencies of working only allowed half the amount to be secured, even then the extra cost of the recovery plant would soon be covered; moreover, a fairly large producer has a wide working range, that is to say, the fuel put through may be reduced from 24 tons per day to as low as 6 without very much lowering the value of the gas, and with certainly no detriment to the ammonia yield, while, on the other hand, if the output has to be forced and the ammonia falls off, the value of the gas somewhat increases.

It is not quite clear from the drawings whether anything in the nature of a ring main for the gas is provided in the engine house. The safest arrangement in view of possible interruptions to the supply would be to divide the producers into two separate groups with distinct mains, offering each engine an alternative source of supply. With a small installation of eight producers this might in some ways be inconvenient, but where the groups are larger this certainly ought to be done; and, indeed, one would be inclined to go further and arrange the blowers in two sections which could also be operated separately.

Although no specific mention is made of the fact, it is presumed that the spare blowers are steam driven, or, anyhow, that steam-driven and electric-driven blowers are provided as alternatives.

It must always be remembered that the essence of safely operating a large gas plant depends upon the ability of being able to

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keep up a continuity of pressure in the blower house even in the presence of a serious leak, and although water lutes are a necessity in a plant of this kind, they should be designed of ample depth, so that they will not prematurely blow in the event of having to increase the pressure in emergencies. Mr. Allen.

It will be noticed that the authors provide for steam-driven exciters, but the blowers, air compressors for starting, and the lighting circuit of the station should also be capable of being driven by independent coal-fired boilers, particularly if separate groups of producers are not provided.

The steam from the small engines can be used for working the sulphate evaporating apparatus, and any surplus turned into the producers or used for heating the buildings in winter.

The bulk of the extraneous low-pressure steam required for the producers would, of course, be produced by exhaust heated steam boilers, which also act as effectual silencers to the gas engines.

Beyond the alternative steam-driven plant already referred to there is absolutely no necessity for spare steam plant in the place, at least this is the writer's personal experience extending over 6 years with a 10,000-H.P. Mond recovery plant, and many large gas-driven stations can be seen in Germany which are absolutely without any reserve in the way of steam.

The writer entirely agrees with the authors as to the size and speed of the engines recommended, be they either 4-cycle or 2-cycle. Engines running at from 90 to 100 revs. per minute seem to have found most favour on the Continent, and give singularly little trouble.

The Snow pump gas engines working in California give 5,400 H.P. with four cylinders, and some Korting engines are now being constructed in Germany intended to develop 2,200 H.P. in a single cylinder. A combination of these arranged twin tandem would produce 8,000 H.P., but the station would have to be a very large one to justify this being adopted as the unit.

From the gas-consumption point of view alone, perhaps the most economical arrangement is to have fair-sized units, say 3,000 H.P. each, and then one or two other smaller engines which are multiples and sub-multiples of the main unit, the smaller ones being put on and off as the load varies. The writer has found this very convenient in a continuous-current station, but it involves a good deal of switchboard attention, and on the whole the arrangement proposed by the authors would seem to meet the case both as to the size of the units and facilities for dealing with the various loads.

As far as repairs and renewals are concerned, the writer has looked up some actual figures and finds that the change from steam to gas effected a saving of about £30 a week, that is to say, when the steam station was producing 25,000,000 units per annum the repairs and renewals for boilers, pipes, and auxiliaries came to £45 per week. The repairs to the producers, ammonia recovery plant, and auxiliaries are

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Mr. Allen.

now covered by £15 per week, an approximate saving of £1,500 per year.

With regard to antiquation and depreciation of the engines, there is no reason to believe that a large gas engine running at a moderate speed and coupled direct to a generator will depreciate more rapidly than a steam engine.

The writer has had two 700-H.P. 2-cycle engines running for over six years, and the output is as good as the day they were started. The cylinders are fitted with liners, and when in course of years these liners get worn down they will be simply bored out and others fitted in their places.

However, there is one point in connection with the gas-engine station that should be taken into account, and that is, the winding of the generators should be very thoroughly and carefully insulated, preferably in a vacuum impregnating machine, as, whatever may be said to the contrary, the atmosphere in a gas-driven station does have a deteriorating effect on the insulation.

Coming now to the capital expenditure, the figures given of £17·68 per kilowatt installed come out almost exactly the same as those arrived at from the examination of some very close tenders obtained by the writer last year for a 10,000-k.w. plant, and the design could have easily been modified to bring this down to £17, allowing a good margin for contingencies.

With regard to the labour costs given on page 27, it is not very clear whether the authors assume two shifts or three shifts for the drivers and producer hands, and the writer is inclined to think from his own experience that some of these labour figures are rather underestimated. No mention is made of any charges for supervision by a chemist, which is a very desirable thing to have. At Weston Point the whole of the producer recovery plant is worked under the supervision of a highly qualified chemist, and this installation is one out of two Mond plants where the highest ammonia recovery results are obtained.

The writer is not at liberty to give the actual cost of power at this installation, but the figures given by Mr. Highfield last year before the House of Lords Committee may be taken as a safe estimate of the cost of running an 8,000-k.w. plant continuously, and taking into account that the authors assume 12s. as being the price of coal, their estimated generating costs will be found to agree very closely with actual installations where the cost of coal is lower and the yield of sulphate somewhat more.

The overall thermo-dynamic efficiencies given in Table III. are very interesting, and the last paragraph of the paper calls attention to the fact that the gas consumption seems to vary directly with the output, independent of the capacity of the plant, and as a moderate-sized gas engine has the same efficiency as a very large one this is about what might be expected.

A careful examination of Table III. serves to confirm the idea that a

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gas-driven plant consumes only half the fuel of a steam-driven one to put the same current on the switchboard. Mr. Allen.

It is for the accountant and actuary more than the mechanical engineer to determine exactly where this economy of fuel is supposed to be balanced by interest and depreciation and considerations of capital outlay, although it must be admitted that the authors' paper deals with these very points probably as exactly as they can be dealt with. But there is another aspect of the question which, as years go on, will inevitably force itself more and more before public notice, and that is how far any of us are justified by any monetary consideration in putting down plant which will burn any more fuel than the irreducible minimum.

Having once got a gas plant it will be found to have the following advantages over steam :—

First, a producer gas plant with ammonia recovery and efficient gas engines will save nearly half the amount of fuel.

Secondly, we get as a by-product a valuable fertiliser to return to the earth, the selling value of which at present reduces the price of coal by 2s. 6d. per ton.

Thirdly, it helps to contribute to the maintenance of a smokeless atmosphere; and

Lastly, we shall be doing our shivering descendants the minimum of injustice.

ADJOURNED DISCUSSION, FEBRUARY 25, 1909.

Mr. H. A. HUMPHREY: My experience with gas engines for driving dynamos dates back to twenty years ago, but it was fifteen years ago when I put to work the first gas engine for use with Mond gas. In those days no maker of dynamos could be found who would guarantee the running of one of their machines if direct coupled to a gas engine, and one firm, whose name is familiar to all of you, assured me that no generator could be built to withstand the repeated shock from the irregular working of a gas engine, and that the insulation must inevitably break down in course of time. However, when I came to erect the second engine for use with Mond gas, which was one of 150 H.P., I insisted on having a dynamo direct-coupled and taking the risk. The set ran on an electrolytic plant in the same power house with steam sets, and not only proved more economical than the steam plant, but established a record for a non-stop run, having worked continuously day and night on an average load of approximately 100 H.P. for over 180 days without a single stop. Mr. Humphrey.

Later on I was responsible for the ordering of a 450-H.P. gas engine and another of 650-H.P. direct coupled to dynamos. These engines were the first of their size erected in this country. I am prepared to admit that in these early days there were many troubles, and many problems had to be solved; but the main fact stands out that, even with

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Mr. Humphrey.

the heavy repair bill of those days, the results favoured the gas engines, and they were able to hold their own against the steam plant. Since then I have been connected with the installation of a considerable number of large gas engines, and I soon found that, in order to be in touch with the latest developments, I had to pay an annual visit to Belgium and Germany. Although several names stand out prominently in connection with the development of large gas engines in this country, yet one has to confess that it was on the Continent that the really large gas engine of 1,000 H.P. and upwards was first made a success.

In general terms I can endorse many of the statements made and the figures given by the authors of the present paper, but I pass on to one or two points which I think will be of special interest to electrical engineers.

Dr. Rosenberg's paper, which preceded this, and also the present paper, have something to say about the cyclic irregularity of gas engines, but both are more or less content to state the irregularity as a percentage variation of the normal speed. Now, electrical engineers will want to know a great deal more about this cyclical irregularity, which has formed the basis of the refusal of several station engineers to adopt gas engines. To show that the same flywheel is not suitable for different types of engines, as is done in Fig. 6 of the present paper, or that a flywheel suitably chosen for a given engine can bring the speed variation of that engine down to 1/250, as is done in Fig. 15, is not sufficient. The electrical engineer wants to get familiar with the shape of the turning-moment curves, not only for full load but for part load, to see how these curves are affected by the large inertia forces which come into play in gas engines, especially of the tandem type, and to have before him a number of cases of cyclic irregularity and angular deviation curves plotted for actual gas engines of various types fitted with suitable flywheels. For certain more refined calculations it is also necessary to have some of these curves analysed into their harmonics.

I have endeavoured to supply this information, and curves obtained from actual data and representing the latest practice are reproduced in Figs. A to G and Tables A and B.

The steam turbine rose into popular favour about the same time that the large gas engine was making a bid for inclusion in the power house, and in the race between these two forms of prime movers the victory has been chiefly with the steam turbine. Its low first cost, its elasticity, its freedom from cyclical irregularity, the ability to build it in large units, and, perhaps above all, its great simplicity, have accomplished this result. Although an advocate of the use of gas engines, I admire the steam turbine immensely. It appeals to me as an engineer; in fact, it is splendid. But what can we say about steam boilers and condensers? I certainly have not the same admiration for either of these. On scientific grounds I am forced to condemn both boiler and condenser, and, speaking to station engineers who have steam plant, I venture to suggest that they have a very good middle to their plant but two bad ends. Take the boilers for instance—they are wasteful at

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normal load, their efficiency is nearer 70 per cent. than 80, and how often it falls even below 70 per cent.! When forced their efficiency is worse still, and when banked while they stand idle they continue to be sources of considerable waste. For all the valuable fuel which their

Mr. Humphrey.

TABLE A.

WEIGHT OF RECIPROCATING PARTS OF LARGE GAS ENGINES AND ACCELERATION PRESSURES DUE TO THE RECIPROCATING MASSES (THE ACCELERATION PRESSURES ARE THE MEAN OF THE VALUES AT THE TWO DEAD CENTRES), BASED ON PARTICULARS FURNISHED BY THE RESPECTIVE MAKERS.

Firm.	Size of Engine.	Total Weight of Reciprocating Parts.	Weight per Unit of Piston Area. Kg. per Cm^2.	Revolutions per Minute.	$\frac{mr\omega^2}{F}$ Kg. per Cm^2 of Piston.
		Kilogrammes.			
Gasmotoren Fabrik Deutz. (Otto cycle)	2,000 B.H.P. (1,100 mm. × 1,300 mm. double-acting tandem)	23,700	2·06	94	17·10
Erhardt & Sehmer (Otto cycle)	2,000 B.H.P. (1,150 mm. × 1,300 mm. double-acting tandem)	20,000	2·06	94	13·25
Nürnberg (Otto cycle)	1,000 B.H.P.	7,200	1·64	125	14·30
	1,200 B.H.P.	8,600	1·57	107	10·80
	500 B.H.P.	3,500	1·21	128	8·31
Premier (Otto cycle)	1,200 B.H.P.	7,220 (two single-acting tandem sets)	1·585	120	10·70
Mather & Platt (2-cycle)	1,000 B.H.P. (2-cycle Korting)	2,687	0·95	110	6·44
Richardsons, Westgarth & Co. (Otto cycle)	1,000 B.H.P. (double-acting tandem)	7,250	1·24	107	7·92
	500 B.H.P. (double-acting tandem)	3,600	1·40	125	9·80
Bechem & Keetman (Otto cycle)	1,000 B.H.P. (double-acting tandem)	3,040	0·78	107	5·00
Snow Steam Pump Works (Otto cycle)	5,400 B.H.P. (double-acting twin-tandem)	20,500 (total mass per line)	2·63	88	17·35

voracious appetite demands they return you nothing in the way of by-products. The fact that thousands of tons of ammonia are destroyed every year in a single large boiler installation may not at the moment afford station engineers much concern, but the conservation of this ammonia is undoubtedly becoming a matter of ever increasing importance.

The gas producer can beat the boiler at every point; it is more efficient, more scientific, more elastic in its working, more responsive to demands, and less wasteful when idle. It is simpler to work and

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Mr. Humphrey.

less dangerous, and requires less repairs. When an opportunity offers of working it in conjunction with an ammonia recovery plant it yields an amount of sulphate of ammonia generally exceeding in value the total cost of the coal. One speaker from Yorkshire suggested that a gas producer would not stand an overload, but if one allows, as is done in practically all kinds of plant, a rather less commercial efficiency on overload, then I know of no limit to the overload of a gas producer, except that in which so much air and steam are forced through that the dust and small pieces of coal are lifted out of the producer along with the gas. The same speaker suggested that the cost of suitable producer fuel ought to be taken higher than the cost of boiler fuel. My experience does not confirm this. As a consulting engineer I am not free to give figures from my clients' plants, but I will take some figures just published by the South Staffordshire Mond Gas Company, and I find that the average cost of 28,952 tons of coal used in the producers was £10,216, including all dues, carriage, unloading, and all expense of depositing same into bunkers, which gives an average cost of 6s. 9d. per ton for all the kinds of coal purchased for the producers. The average heating value is approximately 12,000 B.Th.U. per lb., and I am satisfied that this price is below that of suitable boiler coal having the same calorific value, and purchased in the same district.

While speaking of the South Staffordshire plant, which started working nearly four years ago, I would like to point out that since the commencement of the supply of producer gas under pressure from the central station at Dudley Port, an absolutely continuous supply has been given. The pressure has been maintained in the distribution mains without any interruption, thus illustrating the absolute reliability of gas producers. Again, the gas is so easily and so well cleaned that no trouble whatever of any dirt collecting in the many miles of underground distribution pipes has been experienced, and no traces of any solid deposit have been found in them.

Now turn for one moment to the condensers in connection with steam plants. We give every pound of the working medium in the boiler some 900 B.Th.U. of latent heat, in order to throw them away again in the condenser in a form which constitutes a practical nuisance, and which demands much capital cost in cooling towers to get rid of it. Of course the diagram of the gas plant prepared by the authors shows that that also is not free from cooling towers. That is quite true, but to a less extent. Unfortunately there is no such thing as a perfect heat engine, but, instead of having a steam plant which rejects unutilised, in one way or another, 85 per cent. of the heat, it is better to have a gas plant which is capable of utilising more than twice the amount of heat from the same weight of fuel.

The ideal station plant would be a combination of gas producers with a gas turbine, but, unfortunately, the advent of the gas turbine is looked upon as so remote that the authors do not even mention its possibility.

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FIG. D.

Curve No.	Harmonics. 3rd.	4th.	5th.
1	$\cos(3\theta + 93^\circ)$ 0·473	$+ 1{\cdot}425 \cos(4\theta + 223^\circ)$ 0·407	$+ 0{\cdot}370 \cos(5\theta + 233^\circ)$ 0·106
2	$\cos(3\theta + 94^\circ)$ 1·26	$+ 0{\cdot}778 \cos(4\theta + 240^\circ)$ 0·458	$+ 0{\cdot}180 \cos(5\theta + 201^\circ)$ 0·106
3	$\cos(3\theta + 176^\circ)$ 2·28	$+ 0{\cdot}678 \cos(4\theta + 8^\circ)$ 0·753	$+ 0{\cdot}303 \cos(5\theta + 17^\circ)$ 0·337
4	$\cos(3\theta + 175^\circ)$ 0·529	$+ 1{\cdot}3 \cos(4\theta + 41^\circ)$ 0·372	$+ 0{\cdot}315 \cos(5\theta + 7^\circ)$ 0·09
5	$\cos(3\theta + 175^\circ)$ 1·19	$+ 0{\cdot}690 \cos(4\theta + 60^\circ)$ 0·406	$+ 0{\cdot}089 \cos(5\theta + 40^\circ)$ 0·052
6	$\cos(3\theta + 180^\circ)$ 2·29	$+ 0{\cdot}602 \cos(4\theta + 45^\circ)$ 0·666	$+ 0{\cdot}19 \cos(5\theta + 27^\circ)$ 0·211
7	$\cos(3\theta + 168^\circ)$ 0·151	$+ 1{\cdot}487 \cos(4\theta + 45^\circ)$ 0·425	$+ 0{\cdot}342 \cos(5\theta + 42^\circ)$ 0·098
8	$\cos(3\theta + 138^\circ)$ 0·288	$+ 1{\cdot}43 \cos(4\theta + 46^\circ)$ 0·409	$+ 0{\cdot}276 \cos(5\theta + 52^\circ)$ 0·079
9	$\cos(3\theta + 126^\circ)$ 0·147	$+ 1{\cdot}052 \cos(4\theta + 54^\circ)$ 0·365	$+ 0{\cdot}239 \cos(5\theta + 54^\circ)$ 0·045
10	$\cos(3\theta + 135^\circ)$ 0·313	$+ 37{\cdot}8 \cos(4\theta + 62^\circ)$ 0·298	$+ 6{\cdot}4965 \cos(5\theta + 76^\circ)$ 0·051
11	$\cos(3\theta + 180^\circ)$ 0·114	$+ 30{\cdot}51 \cos(4\theta + 41^\circ)$ 0·504	$+ 6{\cdot}772 \cos(5\theta + 15^\circ)$ 0·112
12	$\cos(3\theta + 132^\circ)$ 0·062	$+ 59{\cdot}85 \cos(4\theta + 41^\circ)$ 0·404	$+ 11{\cdot}69 \cos(5\theta + 72^\circ)$ 0·006
13	$y = \cos(3\theta + 280^\circ)$ 0·205	$+ 354{\cdot}35 \cos(4\theta + 227^\circ)$ 0·0114	$+ 3{,}378{\cdot}0 \cos(5\theta + 86^\circ)$ 0·109

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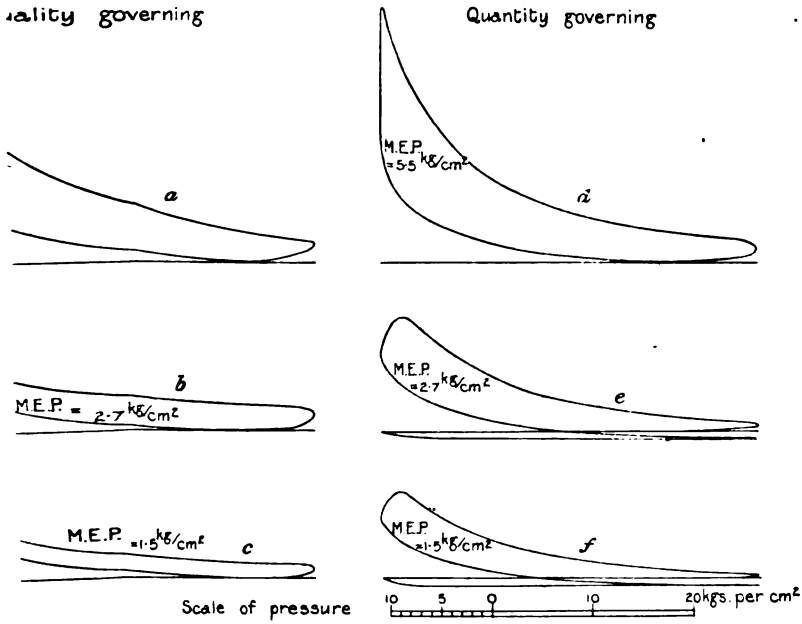

icator diagrams used for constructing turning moment curves

› crank, 5 : 1. Weight of reciprocating parts, 23,700 k.g.
›n area, 17·1 k.g. $\left(=\frac{M\omega^2}{r}\right)$.

N FABRIK DEUTZ.

'Y GOVERNING.

› due to indicator diagram pressures per cm.²
cm.² mean effective pressure of diagram.
›er cm.².
›er cm.².
:as 17·1 kg. per cm.² (actual value).

s.

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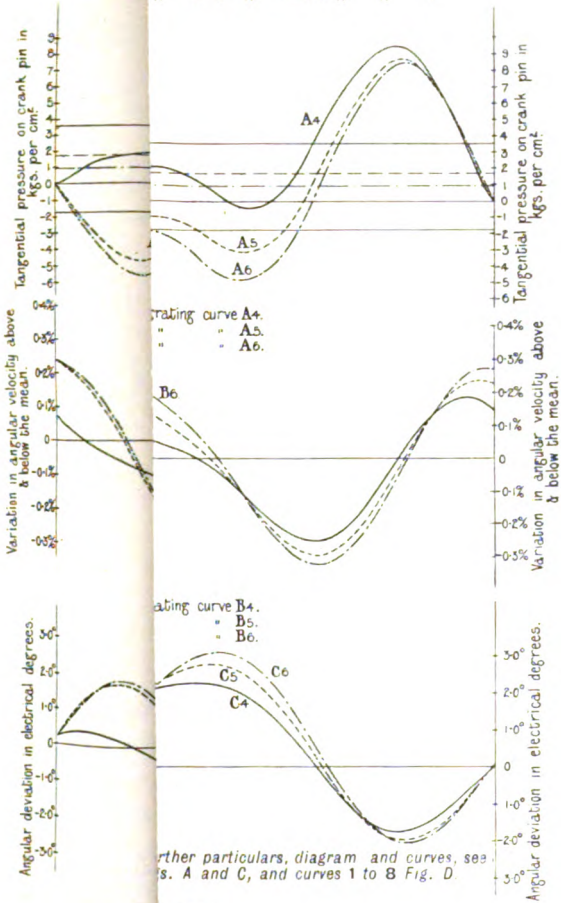
verning.

Curve Fig. A (M.E.P. = 5·5 kgs. per cm.²)
" " A (" = 2·7 " ")
" " A (" = 1·5 " ")



rating curve A4.
" " A5.
" " A6.

ating curve B4.
" B5.
" B6.

rther particulars, diagram and curves, see
s. A and C, and curves 1 to 8 Fig. D

e means.

Tangential crank pin pre
Angular velocity curves
Angular deviation curves
of 4° (electrical) .

he forces due to the inertia are algebraically added.
ocity.
Weight of flywheel to give total angular deviation

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Mr. Humphrey.

Thirteen years ago I studied the problem of gas turbines pretty thoroughly, at the request of those who were prepared to spend a good deal of money on experiments if my report had been sufficiently encouraging. At that date I could not advise that even a moderate sum of money should be spent on experimental work. The difficulties

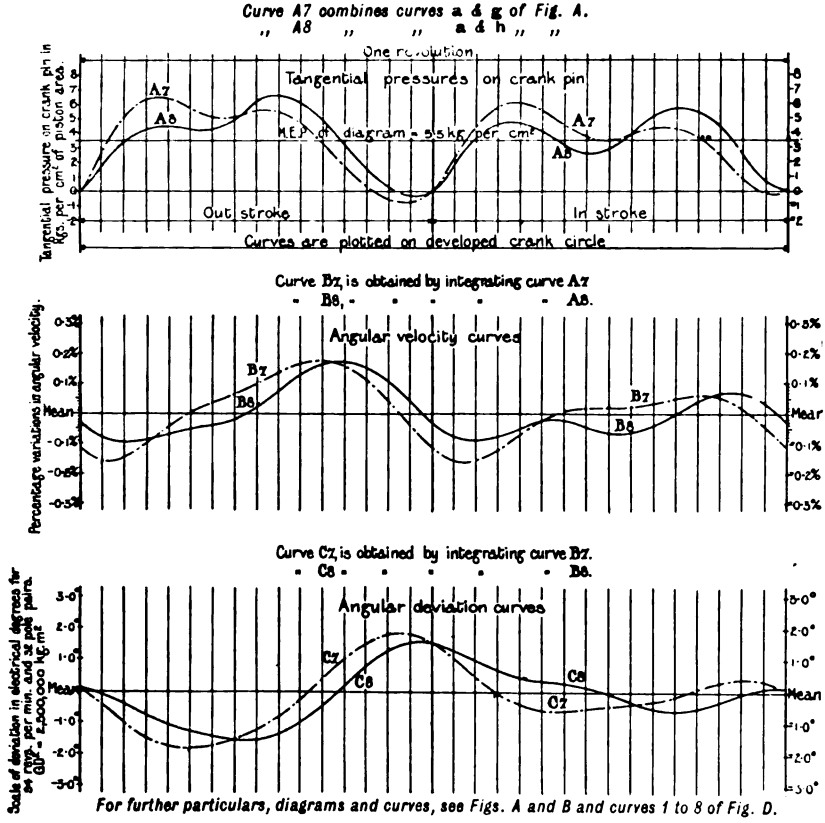
Curve A7 combines curves a & g of Fig. A.
" A8 " " a & h " "
One revolution.
Tangential pressures on crank pin
A7
A8
M.E.P. of diagram = 5·5 kg. per cm²
Out stroke
In stroke
Curves are plotted on developed crank circle
Tangential pressure on crank pin in kgs. per cm² of piston area.
Curve B7 is obtained by integrating curve A7
" B8 " " " " A8.
Angular velocity curves
B7
B8
Mean
Percentage variations in angular velocity.
Curve C7 is obtained by integrating curve B7.
" C8 " " " " B8.
Angular deviation curves
C7
C8
Mean
Scale of deviation in electrical degrees for 64 revs. per min. and 32 pole pairs. GD² = 2,500,000 Kg.m²
For further particulars, diagrams and curves, see Figs. A and B and curves 1 to 8 of Fig. D.

FIG. C.—2,000-B.H.B. Double-acting Tandem Gas Engine (Deutz).

Curves A7 and A8 in this Fig. are directly comparable with curve A1 in Fig. B, and show the effect of combining the full-load tangential pressure of curve A (quality governing) with the reduced inertia forces obtained from curves *g* and *h* in Fig. A.

were too great. Since then I have always been on the look-out for some fresh discovery which might come to the assistance of the gas turbine, and have once or twice had my hopes raised to a rather high pitch, but in the end they have always been disappointed. Still, I do not doubt that the problem will eventually be solved, and at the present time I am making experiments which promise a large measure

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Mr. Humphrey.

of success, although in a direction widely differing from anything previously contemplated. I have at work an apparatus which, by means of gas explosions, forces water into an air vessel, and so puts it under pressure. The water may flow through an ordinary water turbine and back to the apparatus to be used over and over again. I cannot call the apparatus an engine, for in reality it is a pump, but it fulfils all the cycles of a gas engine, and in a much more perfect manner. It does not work on the Otto cycle, but expands its burnt products right down to atmosphere. The gas explosions take place directly in contact with a column of water. This column of water constitutes the flywheel, and all gearing between the working medium and the flywheel is therefore eliminated. There is no solid piston, no connecting rod, bearings, or solid flywheel, no two-to-one gearing, no packing or stuffing box. The explosion chamber is a perfectly plain vessel, without any water jacket, and there is no valve in the delivery pipe to the air vessel. The column of liquid, moving outwardly under the action of the explosion, draws in behind it fresh liquid and a fresh combustible charge, and the latter is compressed before ignition by the column of liquid which tends to return under the pressure from the air vessel. The four strokes of admission, compression, expansion, and exhaust, are all unequal as theory requires, and are all brought about and controlled by the inertia of the column of liquid alone. The apparatus is exceedingly simple and works with freedom from shock and noise, and a small apparatus of only a few horse-power has given a water horse-power-hour for 2 lbs. of cheap bituminous coal. In larger plants I expect to greatly lower the coal consumption, and if I can accomplish this end I shall be far advanced on the road of producing the cheapest and simplest power plant in existence, and one that can be built in very large units.

I will conclude my remarks with a reference to the use of large gas engines for driving alternators, by pointing out that it is a mistake for such purposes to demand that the gas engine should be very closely governed. A speed variation of 6 per cent. between no load and full load is better for running alternators in parallel than a speed variation of only 2½ per cent. There should be no spring couplings of any sort between gas engines and alternators. I find that a rigid coupling is much the best and the safest.

Mr. Highfield.

Mr. J. S. HIGHFIELD: I have had reason for the last eight years to look very carefully into the question of the use of gas engines for power plant. I am quite satisfied that the difficulties in running gas engines are at the present moment distinctly greater than the difficulties of running steam engines; and I should like to say incidentally that I believe the difficulties of running reciprocating engines to be at the present moment less than the difficulties of running steam turbines. I think the reason for this is that there are very few men in the country, either workmen or more skilled engineers, familiar with the running of the plants; and I think in view of that fact, and also

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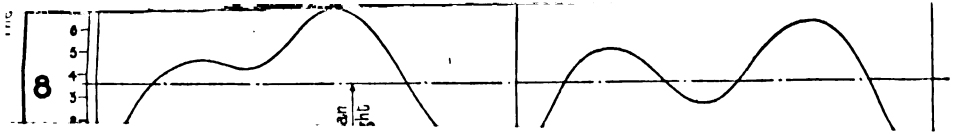

Curve **8** is for the same load as Curve **1**, the only difference being that it combines curves *a* and *h* of Fig. **A**, *i.e.*, a mass (calculated to give the best results) intermediate between the actual mass and

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Mr
Hi

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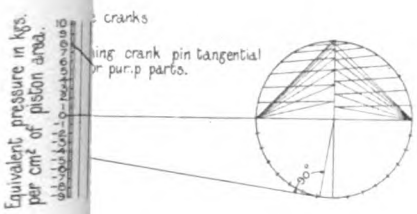
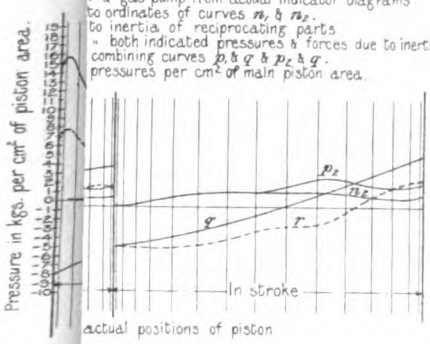
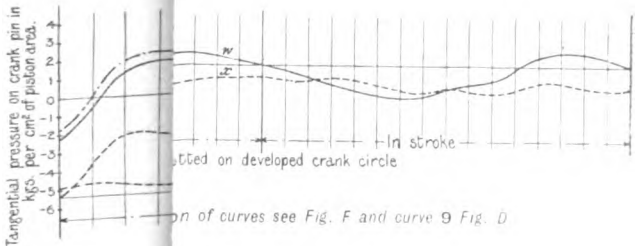


actual indicator diagrams.
r & gas pump from actual indicator diagrams
to ordinates of curves n_1 & n_2.
to inertia of reciprocating parts
" both indicated pressures & forces due to inertia
combining curves p & q & p_2 & q.
pressures per cm² of main piston area.



actual positions of piston

re curves for pump cylinder:
Curve u gives
" v "
" s "
" t "
or one set of pumps due to indicator diagram pressures & inertia forces
both sets " " " " " " " " " "



tted on developed crank circle

on of curves see Fig. F and curve 9 Fig. D

with Cranks at 90°.

Diagrams and Revs., 110 per minute. Air and gas pumps, 650 mm
diamet line of pump parts, 623 kg. $\left(\frac{Mv^2}{r} = 1{\cdot}27 \text{ kg. per cm.}^2 \text{ of}\right.$
main I

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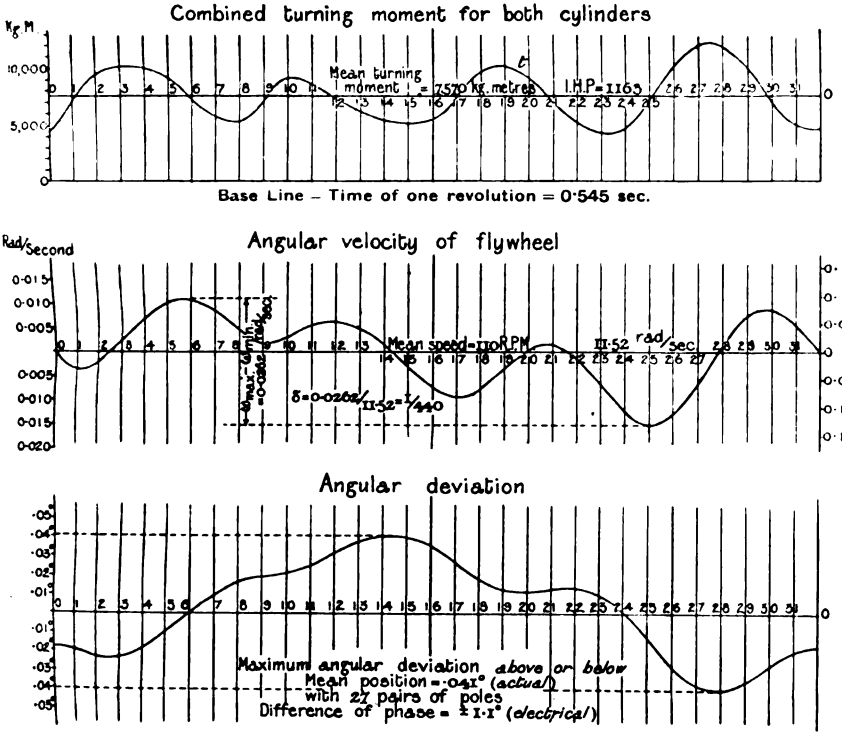

FIG. F.—1,000-B.H.P. 2-cycle Körting Gas Engine.

(Messrs. Mather & Platt, Ltd., Engineers.)

DIMENSIONS OF ENGINE—

Twin double-acting cylinders. Cranks at 90°.
Main cylinders: Diameter, 600 mm. Stroke, 1,000 mm.
Pump cylinders: Diameter, 650 mm. Stroke, 850 mm.
Revs. per minute, 110.

FLYWHEEL—

Alternator rotor equivalent to 28 tons at 11·9 ft. diameter.
G.D.^{2} = weight × diameter^2 = 3,957 ton-feet^2 = 374,000 kg.-metres^2.

CALCULATION OF DEGREE OF IRREGULARITY—

Notation—

M = Difference between turning moment on crank and mean resisting torque in kg m.
I = Moment of inertia of flywheel (mass × rad. of gyration^2) in kg.-metre sec.^{2}.
g = Acceleration due to gravity = 9·81 metres sec.^{2}.
G.D.^{2} = Moment of flywheel in kg.-metre^2.
ω = Angular velocity in rad./sec.
t = Time in seconds.

$$\delta = \text{Degree of irregularity} = \frac{\omega_{max.} - \omega_{min.}}{\omega_0}.$$

$$M\,dt = I\,d\omega = \frac{G.D.^2}{4g}\,d\omega \qquad \omega - \omega_0 = \frac{4g}{G.D.^2}\int M\,dt.$$

$$\text{Angular Deviation} = \int (\omega - \omega_0)\,dt.$$

TABLE OF FLYWHEEL WEIGHTS.

Mean Rim Speed.	75 Feet Sec.			90 Feet Sec.		
δ	$\frac{1}{280}$	$\frac{1}{300}$	$\frac{1}{320}$	$\frac{1}{280}$	$\frac{1}{300}$	$\frac{1}{320}$
G.D.^{2} ft.^{2} tons ..	2,250·0	2,700·0	3,145·0	2,250·0	2,700·0	3,145·0
D ft.	13·0	13·0	13·0	15·6	15·6	15·6
D^2	169·0	169·0	169·0	244·0	244·0	244·0
Rim weight G, tons..	13·3	16·0	18·6	9·2	11·0	12·9
Total weight	18·0	21·6	25·1	12·4	14·9	17·4

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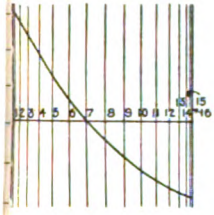
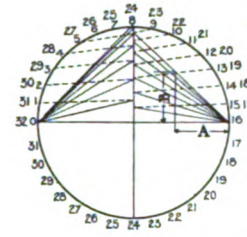
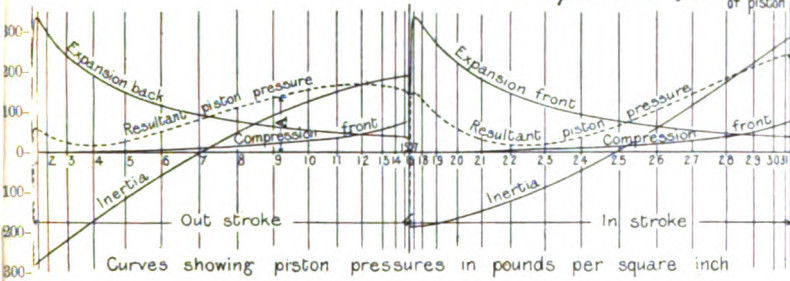


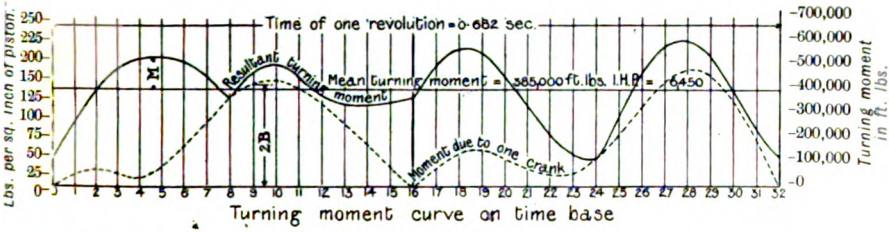


5,400 B.H.P. Gas Engine
four-cylinder double acting twin tandem
The Snow Steam Pump Works Buffalo N.Y.

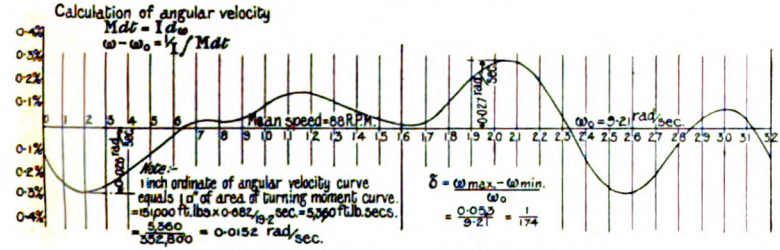
Dimensions of engine
Cylinders Stroke = 60"
Bore = 42"
R.P.M. = 88
Ratio of length of connecting rod to crank 5:1
Flywheel alternator
Moment of inertia = $\frac{W}{2} \cdot R^2$ = 352,800 ft. lbs sec²
Number of pairs of poles = 54
~ per sec. 25
Volts 13,200
M.E.P. of indicator diagram = 99 lbs/□"
Weight of reciprocating parts for one line of cylinders & including ⅔ of weight of connecting rod = 45,500 lbs.
Value of $\frac{Mf}{p}$ for each line of cylinders = 247 lbs. per sq. in. of piston area.



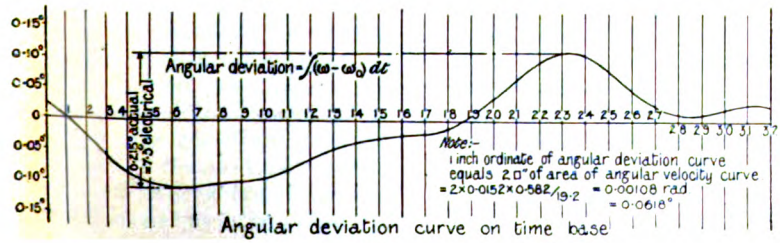
Curves showing prston pressures in pounds per square inch


Time of one revolution = 0·682 sec.
Mean turning moment = 385,000 ft. lbs. I.H.P. = 6450
Resultant turning moment
Moment due to one crank
Lbs. per sq. inch of piston
Turning moment in ft. lbs.

Turning moment curve on time base


Calculation of angular velocity
$Mdt = Id\omega$
$\omega - \omega_0 = \frac{1}{I} \int Mdt$
Mean speed = 88 R.P.M.
+0·027 rad/sec
−0·025 rad/sec
ω_0 = 9·21 rad/sec
Note:- 1 inch ordinate of angular velocity curve equals 1·0" of area of turning moment curve. = 151,200 ft. lbs × 0·682/19·2 sec. = 5,360 ft. lb. secs. = 5,360/352,800 = 0·0152 rad/sec.
$\delta = \frac{\omega max. - \omega min.}{\omega_0}$ = 0·052/9·21 = 1/174

Angular velocity curve on time base


Angular deviation = $\int (\omega - \omega_0) dt$
0·215° actual = 7·5° electrical
Note:- 1 inch ordinate of angular deviation curve equals 2·0" of area of angular velocity curve = 2 × 0·0152 × 0·682/19·2 = 0·00108 rad = 0·061°

Angular deviation curve on time base

FIG. G.

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Mr. Highfield.

the fact that the manufacturers are still feeling their way with regard to the design and construction of gas engines, it would be a mistake to endeavour to apply gas engines on a very large scale to power-station use. At the same time, taking small stations, such as one or two put up by my friend Mr. Wigham, like Guernsey and Ryde, where the whole of the plant consists of gas engines, although admittedly the repair costs are higher than the costs of steam engines, the service given from those engines is entirely satisfactory. I think, therefore, for supplying a lighting load in districts where coal is cheap it is absurd at the present day to speak of gas engines. I think if any engineer put in gas engines for such a load in such a district he would be taking quite unnecessary risks that are not worth taking. On the other hand, if a large supply is to be given for the purposes of running a chemical works, or any similar load where the plant has to be run at 80 per cent. load factor or more, then I think the gas engine must be considered. It is only necessary to see Mr. Allen's plant at Western Point to appreciate that a gas-engine station can be run with bituminous coal worked in a producer properly designed for its use. Mr. Allen has taken out the whole of his steam plant gradually—I am not quite sure whether he told you this on the last occasion—and has replaced the whole of it with gas engines. The service is run in a satisfactory way, and in place of using 2¼ or 3 lbs. of coal, which would be necessary with a steam plant, he can run with roughly 1·7 lbs. of coal and get back approximately 7s. per ton for the by-products. Such a result appears to me to show conclusively, especially having regard to the fact that the best efficiency we can get out of coal with steam engines is about 10 per cent., that for long-hour work or for other requirements where the cost of coal is the dominating part of the cost of the supply, the gas engine will certainly be used to an increasing extent, and it is absurd to imagine that the steam engine will never be superseded. I think for central-station work—and that is the matter I have had specially to consider—the gas engine must be used only in part in the first instance. I have had a great deal to do with the supply of electrical energy to London in one way or another; I have had most of the figures before me, and if you take the London load as it exists to-day and divide into ten equal parts the total amount of plant necessary to run the whole load, you find that the plant necessary to run one-tenth of the whole of the London load turns out 40 per cent. of the whole output, and that half of the plant turns out approximately only 7 per cent. of the whole output. These figures and conditions, of course, apply approximately to any other town and its electrical supply. My own opinion is that the proper way to introduce the gas engine is not to put up a huge station to run at a moderate load factor, say 20 or 30 per cent., but to bring in a certain proportion of gas-driven plant and use that day and night for running as much of the load as possible, and gradually to alter the design of the steam plant so that it can be steamed up rather more quickly than at present, and as far as possible to reduce the stand-by losses. In that way I think the gas plant will be introduced, and I believe it must tend

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Mr. Highfield. to great economies of generation. But I am sure it is most necessary to bear in mind at the present time that the difficulties of putting up a gas plant are that there are few men used to running it, and that all sorts of troubles will crop up in the early stages. There is no doubt that a certain amount of standby plant is necessary, preferably steam plant, to take the place of the gas engine when it fails and when it gives trouble in the first six months of its use. After that I think the difficulties will gradually disappear. Therefore I hope the gas engine advocates will be extremely careful to put them in only when they can show really good results and when they have a fair chance. In this way steady progress will be made in the use of a machine which enables the useful employment of a far greater percentage of the energy contained in the fuel than can ever be obtained by the steam engine. It is a very satisfactory thing that a large number of engines are being built in this country both of the slow-speed and horizontal types, used chiefly on the Continent, and that some makers have succeeded in turning out a satisfactory vertical engine of considerable horse-power, and also that our makers are ready to meet the ever increasing demands for gas engines of various types.

Mr. Sehmer. Mr. E. G. SEHMER: I thank you, sir, very much for giving me the opportunity of taking part in this discussion. As the time is very limited, I must restrict myself to a few remarks about the paper and the discussion. First of all, there is one point that several speakers in the discussion have referred to to which I should like to allude, and that is that the overload capacity of gas engines is about 10 to 12 per cent. I do not quite agree with them in that statement, because the gas engines that are built now give about 10 to 12 per cent. overload continuously, and can work about two hours with 20 per cent., and even more, overload. Then there is the question of producers. We in Germany have not very much experience with producer work, because we have so much blast-furnace gas and coke-oven gas at our disposal, and our fuel is rather high in price. But we have made tests, because we think the gas producer is coming in for gas-engine work. We have made tests with that kind of fuel which cannot be used under boilers, *i.e.*, slaty refuse and coal dust mixed with water from the washing and screening plants, and we have had very good results. For example, the gas from one producer which has been running with this mixture of partly coal dust and partly slaty refuse for twelve months has been examined, and has been found to give about 120 B.Th.U., and I should not hesitate to use it in the gas engine whenever it is wanted. Then there is the question of the price of fuel. Mr. Humphrey has already stated that the price of 12s. per ton for gas-producer coal is rather too high. From what I know of the producers working in this country I quite agree with him in regard to that. I know several plants where they use coal at just about half the price, which is giving very great satisfaction. One of our engines in this country is running on Mond gas from coal which cost about half that price—only about 6s. There is another statement with which I cannot entirely agree, and that is

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Mr. Schmer.

that the capacity of gas engines per cylinder can only be 1,000 or 1,500 H.P. We have built several engines with a capacity of 1,600 B.H.P. per cylinder, and I think twelve of these cylinders are running. We are now designing an engine which will give over 4,000 B.H.P. in two cylinders—that is, over 2,000 in one cylinder. The demand up to the present has not been for large engines, but with the increase of the Bessemer plants in Germany we have to face that question, and we are just designing an engine which will give above 8,000 H.P. with four cylinders for a Bessemer plant. Several remarks are made in the paper, and have been made in the course of the discussion, about the cost of repairs. I must say I do not quite see why everybody should doubt the percentage given, which has been based upon information carefully collected by the authors from firms using gas engines. I should be quite prepared to guarantee that the cost of repairs would not exceed, in a case like the one taken in the paper of a station of 10,000 k.w., £2,000 or £2,500, including all the repairs—everything—for the cleaning plant, generators, producers, and everything else. Then several of the speakers have mentioned that the price of gas engines is too high. The gas-engine builders, of whom I unfortunately am one, have spent an enormous amount of money in experimenting. Of course this must be brought back in some way, and considering the very small number of engines which have been built up to now, the amount for each engine is rather high. But prices have come down very quickly already, and I am sure the time is not very far distant when the difference between the price of an ordinary steam engine and a gas engine will not be very considerable. There is one other point to which I should like to refer, namely, the capital cost, or the first cost, of the gas engines given by the authors. I think that price is rather high. I should certainly be quite prepared to take any amount of orders now at a considerably lower price.

Professor Threlfall.

Professor R. THRELFALL: The authors have done their best to make a comparison between a turbine installation and a gas-engine installation. I should think it is absolutely impossible, even with the best intentions, to select conditions which would apply fairly to all places. One point that strikes me particularly is that we have heard nothing in the paper about the amount of ammonia that is to be got out of the coal. I have just roughly divided out the figures, and it looks to me as if something like 90 lbs. of sulphate of ammonia is expected per ton of coal. I do not know how many places there are in England where that can be obtained if 12s. a ton is paid for coal. That is a point which I think makes it somewhat difficult to come to a decision. I daresay that for 12s. a ton coal can be obtained almost anywhere, but 12s. a ton is an altogether outside figure. In an industrial district nobody dreams of paying that price for coal. If we come down to ordinary prices, the South Lancashire district is about the only place where to my knowledge it is possible to obtain 90 lbs. of sulphate of ammonia per ton of coal, because we must remember that it is not every kind of coal that will do in a producer. We talk

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Professor Threlfall.

about using bituminous coal, but there are a great many bituminous coals that cannot be used, or can only be used in an admixture with other kinds of coal. If it is necessary specially to limit the coal so that the coking power is not too high, I think it will be found a very difficult matter, except in one particular district, to get a coal that will give 90 lbs. of sulphate of ammonia per ton of coal at a price approximately near to that at which fuel in the district can be bought for use with boilers, and this is really the standard of comparison. That brings me to another point. I do not see in these estimates—it may be there, but it is not apparent—any proper allowance for the raising of the steam which is necessary to work the producer plant. Perhaps reliance is placed to a great extent on the regenerator boilers which take the heat from the gas engines. Where the plant is worked with a variable load, those engines that have just come on will not raise steam at once because the boilers take some time to get hot, and the consequence is that we should have to raise some steam elsewhere; but there is no provision made for that in these estimates. The matter is further complicated by the fact that less steam is required if the ammonia is not recovered. With regard to the item of repairs of engines, which has been referred to so often, some people have had a good experience, and others have had a bad experience. I think the sum put down in the paper is about the best that we can hope to do. Coming to the producer plant, I see there is an allowance for repairs of 6d. a ton. I think that is a good deal too low. There is one other point I wish to refer to, namely, the reliability of the gas engine. Mr. Humphrey has told us about the phenomenal running of an engine at Winnington as far back as 1899 or 1900. I have long felt that that was the most unfortunate thing that ever happened in the history of producer-gas engineering. It made everybody think that the gas engine was just as easy to drive as an old donkey steam engine, but this is not at all the case. It turned out afterwards that it was a totally exceptional thing, and not at all the rule, to be able to run gas engines in that manner. One word as to the present position of the gas engine. I think it is excellent. I think the makers have got everything right now; one maker or another has made everything right, except that we always have the stuffing-box and the cylinder with us, and there is always the possibility of trouble with them. I put it to the gas-engine makers whether it is not advisable to go to very much greater expense in the steel of which their piston rods are made. I spoke to Mr. Drawe about it this evening, and he did not agree with me, but I still think there may be something in the suggestion that makers should buy the highest possible grade of steel with the object of making the piston rod as thin as possible, so that the temperature of the outer surface may be reduced to the lowest possible point. The alternative to that is to reduce the compression in the engine. I think that hitherto we have aimed at too high compressions. If the compression is reduced in any way, the surface temperature of the piston is lowered, and that makes enormously for the comfort and ease of working of the engine. That brings me to the

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only other point left, and that is the life of the cylinders of the engine. This is a question which it must be admitted is still in a state of uncertainty. I do not know myself at the moment which is the best kind of cylinder to have, whether to have a cylinder made all in one piece or made in several pieces. What I do feel, however, is that any engineer who is going to run an outfit of gas engines will be well advised to say to himself when he starts, "I shall break a cylinder every three or four years." I should say that three or four years would be a fair life for a cylinder under 95 per cent. load factor. I think that every year a sufficient sum should be put aside to buy a new cylinder when the time comes, and not to have phenomenal costs one year, something in the neighbourhood of 0·10d., jumping up the next year to 0·40d. because the cylinders have gone wrong. Professor Threlfall.

Mr. J. E. Dowson: I have been advocating the use of gas power for many years, and it is gratifying to see such an important paper before the Institution and to note the keenness with which it is being discussed. It was probably a revelation to several who were here on the last occasion to see illustrations of so many large gas engines actually in use. Unfortunately there is rather a disappointing feature connected with those large engines, and that is that none of them were of British make. In this respect we are behind America and Germany, and I hope that the encouragement some electrical engineers are now giving to the subject will act as an impetus to our English gas-engine builders. Some of the leading makers I have spoken to on the subject have told me that they are prepared to supply engines of 1,000 B.H.P., but for the present they seem to prefer not going beyond this power. If, however, they can go to 1,000 H.P., so far as we can judge from what has been done elsewhere, there seems to be no reason why they should not go beyond that power. I hope, therefore, that what has been said and shown here will bring home to British makers that there is a real future for large gas engines, and that electrical engineers are prepared to adopt them if they are proved to be suitable for their purpose. It should not be necessary to go to America or Germany for them. Reliability is, of course, essential for central-station work, but until larger units than 1,000 B.H.P. have been made and tried in this country for such work I venture to suggest that it will be more prudent to stop at 1,000-H.P. units for the present and to have larger ones later. It should also be remembered that you can have gas plants without the recovery of ammonia. I am not against the recovery system—on the contrary, I have a high opinion of it—but the recovery plant involves a heavy capital outlay, and it occupies a larger ground space than can sometimes be provided. With 1,000-H.P. units you could still use almost any kind of non-caking bituminous coal, or you could use coke, and would get good economy in that way, compared with steam power, with considerably less outlay. I am glad the authors have brought to your notice prominently the question of standby losses. It really is an important question, and it is a little strange that the loss during the Mr. Dowson.

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Mr. Dowson.

long standby hours in central stations should be taken so little account of. When I investigated this subject a short time ago I was surprised to find how little information about it was available. I corresponded with several engineers, and some members of this Institution and others were good enough to make some tests for me, and I gather that the diagrams put forward in the paper are based on the results which I obtained. I hope that those who have charge of steam boilers and have opportunities of determining the fuel consumption when standing will give this matter their attention. I do not quite agree with what Mr. Humphrey said about the low efficiency of a boiler. I have always understood that a well-worked boiler of good design has a heat efficiency of about 80 per cent. at about its full output, but its bad side comes out when it is standing. There is then a large quantity of brickwork and of water which loses heat, and this loss has to be made up again when steam is required. Compared with a steam boiler a gas producer for the same power is small, it contains no water, and its loss by radiation is not nearly so serious when standing with a fire in it. The standby loss with a producer is therefore much less than with a steam boiler.

Mr. Taylor.

Mr. A. M. TAYLOR: With regard to Fig. 10 I think the authors are to be congratulated in bringing forward in such a neat and clear way the question of the true cost of the "additional" units and their connection with the no-load losses of the steam engine.

From the Willans Law diagram we know that a portion of the steam admitted to the engine may be considered as a constant loss, or nearly so, at all loads, while another portion is directly proportional to the load. This latter part corresponds, in a large turbine, to about 14 lbs. of steam or 2 lbs. of coal (10,000 B.Th.U.) per unit generated, whereas in stations employing such turbines the consumption is found to run up to as much as some 3 lbs. or 4 lbs. The difference can only be due to certain losses of a constant nature occurring in boilers, pipework, engines, and auxiliaries; for not more than some 5 per cent. excess can be fully accounted for by likely departures, under average working conditions, from test conditions of steam pressure, superheat, or vacuum.

Also, since the useful part of the steam consumption is independent of the loading up of the sets, it follows that the cost of the "additional" units does not depend on the running plant load factor. It would, therefore, appear to be clear that we may assume that the true cost in coal of the "additional" or "make-up" units is at most about 2·2 lbs. for large turbine units, and in the case of a 500-k.w. reciprocating engine, made by Allen of Bedford, I found from an examination of the test records that it was still as low as the equivalent of 2¼ lbs. of coal, or, say, 2¾ lbs., allowing for reasonable departure in ordinary working from test conditions.

I wish to emphasise that in Fig. 11 the 2 hours' daily duration of the 6,000-k.w. load is an average over the whole year, and at certain periods this load will have a duration of two, or even three times that amount. Reverting now to Fig. 12, I would ask Mr. Andrews whether

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Mr. Taylor.

he has considered the possibility of reducing the number, and increasing the overload capacity of his units by combining them with batteries of accumulators, placed preferably in rotary converter or motor-converter sub-stations. Suppose, for instance, that he put down three gas-driven units, each of 2,000-k.w. capacity, and two battery units, each of the same capacity (see Fig. H); and, for the sake of argument, let us work on the basis which Mr. Jenkin has suggested for spare plant. Then, with one gas set laid up for repairs and one set broken down, the load has to be taken up between the two battery units and the remaining gas engine for two hours. This would involve a 45 per

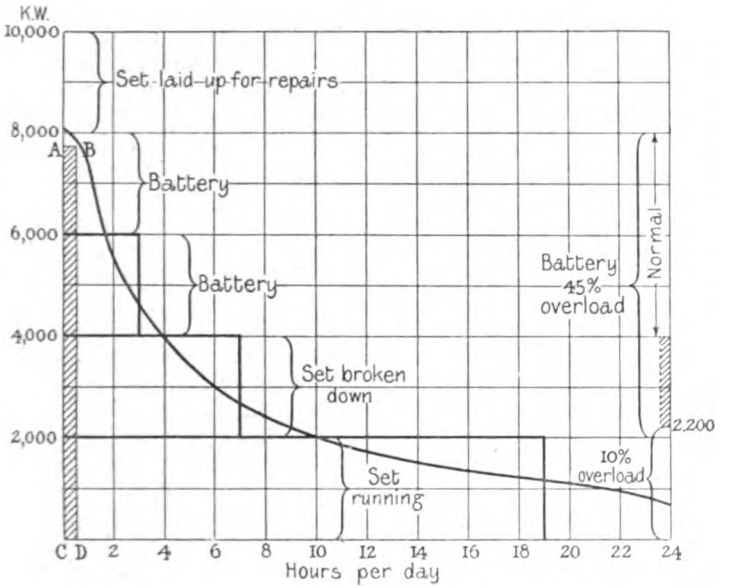

FIG. H.

cent. overload on the two batteries and a 10 per cent. overload on the gas engine. If the batteries were put in for a 3½-hour rating, they would do this overload for 2 hours, as required by Mr. Jenkin's proposal. The batteries and accessories would cost about £11 per kilowatt, as against some £14 for the gas plant plus £6 for feeders and rotaries = £20 total, and the saving in fixed charges would, as I have shown elsewhere, more than suffice to pay the maintenance and depreciation rate twice over. As regards coal, the area dealt with by the battery in normal working would be that above the 4,000-k.w. line, or, say, some 3,600,000 units, out of a total of 21,000,000. Allowing for losses in batteries and auxiliaries, the supplying of these units would involve an extra 1,800,000 units, which, however, being merely a "make-up" load, are only chargeable at the rate of "additional"

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Mr. Taylor.

units and therefore only account for some 900 tons of coal. This is turned into a gain of 900 tons by the fact that the other 3,600,000 also become make-up units, and thus save 1,800 tons; a net gain of 900 tons.

The engine-hours could be reduced to some 9,500 as against 17,450, and the producer-hours from 35,000 to, say, 20,000; which two items would jointly account for a saving of some 1,700 tons of coal per annum, allowing for the fact that the units are larger than those proposed by Mr. Andrews.

The net saving on coal would therefore be some 2,600 tons per annum; the capital saving would be some £36,000. In the case of a transformer sub-station distributing with alternating-current currents at high tensions, this would be reduced to £24,000; and the annual net saving on fixed charges alone (ex. interest) would, I estimate, be at least £8,000 per annum; the whole amounting on a 24 per cent. load factor and with coal at 12s. per ton, to a saving of 0·10d. per unit generated; or 25 per cent. off his estimate for gas plant. In the event of a sudden excess of load falling upon the gas engines, the value of the battery, as providing a means of immediately taking up that excess of load, without having to wait until another engine had been started up, would be very considerable, as it might save a possible breakdown of the remaining engines, if these, through the carelessness of an attendant, had been allowed to run too near their limit. It will also be granted that the battery would be very valuable as a means of enabling the engines and producers to run continually at their full load and so at their highest efficiency, without fear of the overload being exceeded. Without the battery it would be necessary in many cases to run up a second set, entailing not only larger coal losses, but a larger staff in the engine-room. Mr. Andrews' figure (No. 10) is, I think, especially valuable, as embodying in a simple graphical form data on numerous sizes of engines, and emphasising the low cost of the additional units required to load up a set. I am sorry, however, that he has not given us fuller particulars as to his Table I. and his Fig. 13 on pages 31, 32. His figures, which cannot readily be checked, appear to contain an error in the coal item.

Communicated: In the case of such towns as Glasgow, Manchester, etc., where direct-current distribution is carried out from sub-stations a couple of miles or so distant from the main station, the battery would preferably be placed at the sub-station, and would supply into the direct-current busbars through boosters. In this case each unit of steam, or gas, plant at the main station displaced by the battery is debitable with the cost of high-tension feeders (£3 per kilowatt, including spares), with high-tension switchgear at both ends (£1 5s. per kilowatt), with step-down transformers and rotary converters (£3 per kilowatt, including spares), and with the difference in cost between the building required for generating plant and that for the cells and accessories (say, £3 per kilowatt); or a total of some £10 per kilowatt. Thus if the gas plant cost, say, £17 10s. per kilowatt, as estimated by

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by Mr. Andrews, the total cost becomes £27 10s. per kilowatt, as against a battery and accessories costing £11 per kilowatt. In the case of distribution with H.T. alternating currents, a special sub-station would have to be built at a good centre for H.T. distribution, and this sub-station could serve as a linking-up point for H.T. distributors. The batteries and rotaries would merely deliver alternating-current current to the sub-station H.T. busbars; but they would reduce the number of H.T. trunk feeders from the main station to that extent. Consequently, in this case, the generating plant can be debited with cost of high-tension feeders (£3 per kilowatt), and difference in cost between building for generating plant and that for batteries and rotaries (say £2 10s. per kilowatt) or a total of £5 10s. per kilowatt; which, added to £17 10s., becomes £22 10s. per kilowatt, whereas the cost of batteries, step-down transformers, rotaries, and switchgear may be taken as £13 per kilowatt. Mr. Taylor.

The fixed charges with the battery scheme would, however, be increased by some 10s. per kilowatt of M.D. per annum; which must be deducted from the estimated saving of £2 per kilowatt given earlier, leaving £1 10s. as the net saving per kilowatt per annum, exclusive of saving on interest charges on reduced capital.

Mr. G. L. ADDENBROOKE: I have gone into this question of the use of gas engines on several occasions, and would direct attention to a matter at the other end from that with which most of the speakers have been dealing. There is the question of producers working with low loads which must be dealt with in the case of variable central-station loads. If a producer is put in, it cannot usually be loaded up fully unless the plant is put into a central station where there is already a good load. There seems to be a difficulty in working with producers at less than half load. One producer must therefore be provided, whose capacity at half load is less than the smallest central-station load, and the working of the other producers must be also arranged so that they can be cut off below half load, which would seem to require a good deal of manipulation. Another important point not dealt with by the authors, if gas is used in town installations, is the getting rid of the considerable amount of tar-water produced by the cleaning plant, as the authorities object to its being turned either into streams or drains. Mr. Addenbrooke.

On the question of steam *versus* gas stations, I certainly think the authors' figures are too high for the steam plant, and that they have postulated conditions rather against that plant. For instance, in most cases the stations would be selected with better water facilities than are allowed for, and the cost of turbines would also be smaller. On the other hand, I think we owe a debt of gratitude to them for their diagram of the losses in steam plant. That is a subject to which I have given a great deal of attention; and, as one speaker has already mentioned, it is extraordinary how difficult it is to obtain any really organised data on the subject. One can get any number of tests of efficiencies of boilers and turbines and so on at full and half load; but when the whole is combined in a plant, such tests as are made seem to

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Mr. Addenbrooke.

be carried out in a promiscuous manner without any real attempt to get at the bottom of the losses in such a way that they can be effectually tabulated. I certainly think that this diagram is a step in the right direction. I do not quite agree with the way it is drawn, but it is a great point, I think, to take Willans' Law as the basis of all work in finding out what the losses in a central station are. The losses in steam pipes are almost fixed, and the losses in pumps are also very nearly fixed. There is the warming up of the turbines, and so on. Then, again, with regard to the turbines themselves, if we have no load tests of the turbines, which should always be taken, it is possible from the Willans Law to estimate the amount of steam which is used merely to turn them round at any load.

In dealing with the losses in central stations I always try to find what I call the "turning-round factor" as a basis, that is, the amount of coal needed to keep the central station going completely, as it is used in practice, but without including any external work, such as banking of boilers, etc. This with some care can be ascertained by tests on the various portions of the plant. Then if the coal expenditure at a fair load is also ascertained over a few hours, close approximation can be made of the coal per kilowatt needed for doing outside work, and this will be found a pretty constant factor over a wide range of loads. Such figures once obtained can be compared with the station records from time to time, and will be of great assistance in tracing undue losses and keeping down the amount of those that are inevitable.

It is interesting to take out this "turning-round factor" for the steam and gas stations postulated by Messrs. Andrews and Porter. It is, on their figures, 11,100 tons for gas and 15,170 tons for the steam plant, but I consider that with care undoubtedly better results would be secured with the steam plant, so that probably as regards the amount of coal needed to keep both plants going, without doing external work (the steam plant also having a larger overload), there is not very much difference, there being a much greater amount of engine friction and low-load losses in the case of the gas engines, nearly making up for the larger boiler loss from banking, etc., in the case of steam.

As I stated in the lectures which I delivered recently at the Royal Society of Arts, I certainly think there is room for at least 25 per cent. economy in modern central stations over the best steam practice of the day as it exists now, provided that losses in the plant can be thoroughly attended to and reduced by taking advantage of a number of possible refinements. Nevertheless, when all is said and done, the gas engine is undoubtedly coming on. There are places where coal is expensive, and where, with a fair backing from those who are financially responsible, I think an engineer would now be justified in trying gas engines in connection with a steam plant, where there is sufficient overload capacity in the turbines or engines to carry one over a breakdown.

The real gain in the case of gas is in the extra thermal efficiency of the gas engine for the external work done, a point which is not disputable.

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Mr. Addenbrooke.

The authors postulate a gain by ammonia recovery of 90 lbs. per ton of coal used, but it is a fact that certain coals do not give half this. If a list of the leading classes of coal in the United Kingdom suitable for producer work were drawn up by producer makers, giving approximately the amount of ammonia recoverable from each, it would be of great assistance to engineers, as they would be better able to see how they were individually situated with regard to this.

While on the subject of the ammonia recovery plant, is it altogether fair to assume that ammonia recovery is not a commercial possibility with a steam plant? It has for some time been my opinion that boiler practice could be greatly improved by burning the coal in producers and using the gases under the boilers. By designing the boilers properly for this, lagging them, and constructing them to take only the air needed for combustion, the no-load losses would be greatly reduced, and from all information received very efficient combustion of the gas could be secured in the boiler—in fact, its output could be increased—and even if the gas were cooled and the ammonia extracted, it does not seem that the quantity of coal used to produce a given amount of steam would be increased. In this case the difference in cost between gas and steam would be greatly reduced—in fact would nearly vanish in the authors' figures for stations with ordinary load factors and with coal at 12s. per ton. This is what is actually being done now in some of the waste heat stations operated by coke-oven gas after recovery of the by-products. I do not wish to say that there may not be an advantage in the use of gas engines even in these circumstances, but to balance the pros and cons is, I cannot help thinking, at present a more complicated question than the authors have assumed—in fact, one on which it is almost impossible to generalise effectively, as the balance turns on so many side issues that it is only in specified cases, where the conditions of recovery and coal supply are accurately obtainable, that a definite conclusion can be reached. The immense amount of work which is being done on internal combustion engines, especially in connection with the automobile industry, is, however, a factor which must in the long run tell.

It may be of interest to mention that not long ago I went very carefully into the capital and working costs of a gas plant for ordinary power work to give an output of about 1,500 k.w. with additional spare plant. After corresponding with makers and obtaining tenders, the capital cost came to about 33 per cent. more than that of a steam plant, including all buildings, foundations, and everything necessary to make each plant complete. The expenditure of coal on a 25 per cent. power factor came to about 3 lbs. per unit generated, including all standby and other losses, as against 4¼ lbs. for the steam station; and the gain in this respect with coal at 11s. per ton more than balanced a fair interest on the extra capital, though the margin was not so good as that in the paper. There was in this case no ammonia recovery plant.

Mr. Booth.

Mr. W. H. Booth: It seems to me that our friends in Germany have taken up the question of gas engines in a much better way than

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Mr. Booth. we have done. They have their fuel for nothing. They did not put up producers and go in for expensive plant—not that I object to that in any way—but since they got their fuel for nothing, in that way they were able to afford a few breakdowns with their gas engines. If a gas engine broke down, the free fuel helped to pay for the breakdown. I think we should have been wise had we kept the lead which we had over the Germans, and gone in early for the making of big gas engines in this country. If we look round the country at the big gas engines that are installed, we shall find they are mostly of German or Belgian make. Every year we hear of some new foreign engine being put up in this country; the latest one is the Nuremberg, one of the best German gas engines. We are a long way behind now, and we still preserve the *non possumus* attitude. If we go to Germany we shall find that there are several hundred thousand horse-power of reliable gas engines working to-day, and yet we meet here and discuss whether a big gas engine can turn round or not!

Communicated: Three years ago I stated before a Parliamentary Committee that there were no physical or mechanical reasons why gas engines should not be made as big as steam engines, and there seems no good reason to claim 36 in. as the maximum practical diameter of cylinder. Some idea seems to be prevalent that a certain maximum cylinder diameter is rendered necessary by the exigencies of the water jacket. But the function of the jacket is not to gather heat from the burning charge, it is to maintain the inner surfaces cool. The jackets do absorb heat, but this is an unfortunate incidental only. The fire-side of boiler plates does not get much hotter than the water on the other side in spite of a fire of great mass. Can it be supposed that the small mass of hot gas in a cylinder will overheat a cylinder wall, which is after all only like a boiler plate? Yet this idea seems to be the basis of the objections to large cylinders.

If it can be shown that larger masses of gas do give too high a terminal temperature and pressure owing to the reduced absorption per unit of volume of gas of the cylinder wall, it would be possible to obtain present mean pressures from smaller charges of gas, and the larger engine may be more efficient. But, apart from such practical experience as is yet to be gained in the application of larger cylinders, there is surely no rational basis for the claim that the diameter of cylinder has now reached its limit.

Mr. Robinson. Mr. I. V. Robinson: I do not think the position of English gas-engine builders has been fairly and truly represented in the paper now before us. The authors state that a few small engines of 300 to 500 B.H.P. have been running in Great Britain. In 1903, six years ago, the firm with which I am connected built engines of 800 H.P. which are still running, and they have since built a considerable number of larger engines, amongst which are ten of 1,000 H.P. or

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Mr. Robinson.

over; there is therefore no doubt that the English manufacturer can build large gas engines, and will do so as soon as the users of large engines will come forward and place their orders. Like Mr. Sehmer, I am ready to take any number of orders for engines of any size. Most of the points of general interest have already been dealt with, but there are still one or two to which I should like to refer. With regard to speed varation, that is merely a mechanical question and can be settled without difficulty. To my mind what is more important than the speed variation curve is the curve that is deduced from it—viz., the curve of angular variation—which has not to exceed a certain maximum amount on either side of the position attained by a uniformly moving wheel. Mr. Humphrey's curves will probably give all information that will be required on that point. About twelve months ago I worked out, in connection with a paper read before another Institution on the regularity of large gas engines, the case of a twin-tandem double-acting engine having cylinders 18 in. diameter by 24-in. stroke, and running at 180 revs. per minute. This engine was fitted with a flywheel so designed that the energy contained when running at its normal speed was equal to the energy contained in 30 explosive impulses. In this case the flywheel only weighed some 8 or 10 tons, which was comparatively small for an engine which indicated nearly 1,000 H.P. In spite of the small flywheel capacity the maximum angular variation was only 0·07° on either side of the mean, whereas for driving 50-cycle alternators in parallel it would probably be permissible to increase this allowance to 0·27°. As regards the capital cost, I am sorry I cannot agree with the figures put forward by the authors, particularly with regard to the steam turbines. The firm with which I am connected manufacture steam turbines also, so that I know something about the capital cost of them. I would reduce the authors' price from £13 19s. per kilowatt to about £12 11s. with cooling towers or £11 16s. without cooling towers. The gas-engine prices, I think, are correct; if anything they err on the high side. With these corrections the gas plant will cost 40 per cent. more than the steam plant with towers, or 50 per cent. more than the steam plant without towers; and with these revised figures I think that the combination of gas engines and steam turbines in one power station is the right thing. In many stations there is a minimum load throughout the twenty-four hours of 3,000 or 4,000 k.w. In such a station as that, a gas engine should be put in to take up the minimum load throughout the twenty-four hours, and it will show an excellent return upon the capital invested. Then I wish to say a few words with regard to the repairs. Reference is made in the paper, and also in Mr. Allen's recent paper, to the works costs in John Cockrill's works at Seraing. In the year ending March, 1907, the Cockrill Company generated in their own works power station 24 million units. The plant has a total capacity of 8,400 H.P., and that output corresponded to a load factor of about 50 per cent. M. Greiner, the chief engineer of that company, published the following information as to the works

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Mr. Robinson.

costs in a paper read before the Liége Society of Engineers in March, 1907.

Load Factor. Per Cent.	Works Cost per Unit Generated. Pence.
25	0·116
50	0·0625
75	0·0417
100	0·0313

From these figures it will be noticed that the total aggregate works costs are practically the same at all outputs—that is to say, he has not allowed for any decreased amount of oil, repairs, or superintendence for the low load factors. Therefore if we are able to give the gas plant a higher load factor than the one the authors have taken for their example, the gas engine shows up to much greater advantage. Even with the low load factor of 24 per cent., making all the corrections as to capital cost, I still think the gas engine will show up more favourably than the steam turbine. On reference to M. Greiner's figures, I find that his total is 0·116d. per unit for a 25 per cent. load factor as against the authors' 0·102d. Comparing the various items, I find the authors allow 0·036d. per unit for labour, including engine attendance and general superintendence, as against M. Greiner's 0·041d. For cleaning, repairs, and upkeep the authors allow 0·052d., as against M. Greiner's 0·051d.; thus showing, in my opinion, that the authors' figure of £4,000 a year for repairs is a fair one, and has already been carried out in practice. I am afraid that the figure the authors give for oil is rather low according to the figures I have—0·015d., as against M. Greiner's 0·023d. On the whole the authors' figures require increasing by about 10 per cent. for the works charges. These corrections bring the cost of the gas-engine unit to 0·39d., and by reducing the capital charges of the steam plant, the total cost of the electrical power is brought down to 0·462d., as against 0·395d. So that, even with the low load factor of 24 per cent., the gas engine justifies its installation; and if it is put in to deal with the minimum load, and you have a load factor of 80 or 90 per cent., there is no doubt whatever that the gas engine will be the right thing to put in, and I hope that we shall very soon see many such engines installed. I would like to remind all engineers, in conclusion, that there is no need for them to go abroad for engines.

Mr. Stewart.

Mr. V. B. STEWART: I should like to point out to the authors that there is a discrepancy between the statement made on page 5, viz., "There is no material difference in the reliability or in the cost of labour and repairs of the respective systems," and the tables given on page 27. I think the figures given on page 27 for labour on the steam-turbo plant are too low, and should be brought up to their proper level, so as to agree with the first statement made by the authors.

The total capital expenditure given by the authors for steam and

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Mr. Stewart.

gas plants appears to me to be only relatively correct. In the discussion several gentlemen, who have a large experience in turbine installations, have taken exception to the figure of £139,525, given as the cost of installing steam plant for the proposed station, as being too high; and Mr. Fox thinks that £100,000 would more nearly represent the capital expenditure for a modern steam-turbo plant of this size. I am perfectly certain that the estimate for the gas plant and engines can be reduced by an almost equal amount. For instance, the general arrangement shown on Fig. 4, though an excellent one, is extravagant; and the ground area can be very much reduced both for producer and engine plant without in any way taking away from its efficiency. Scaling the diagram Fig. 4, I gather that the producers are placed at 24-ft. centres, whereas in our plants 16-ft. centres have been found to give ample room for efficient working. The figure of £98,000 for seven 1,450-k.w. gas engines, generators, etc., etc., is also a high price, and I should be very satisfied if any one here to-night were to send me back to Glasgow with even a small order at a similar rate per kilowatt. But this would not affect the final comparative figures given by the authors, as the relative excess cost of gas plant to steam plant has been fairly and accurately stated. The authors have erred on the safe side as regards oil consumption, and, from experience, I can say the lower figures are easily obtainable. I may mention in this connection that the average cost of the oil which we use is 11d. per gallon, and the consumption of oil for a year's running amounted to 0·3 gallon per 1,000 H.P.-hour, the cost being, therefore, 8½ per cent. less than the lower figure given by the authors.

One other point, though a small one, to which I should like to refer is the arrangement shown in Fig. 9, whereby the same conveyor which takes coal to the bunkers is utilised for conveying the ashes from the grates of the producers. As a matter of fact, this was an arrangement which we had on the first ammonia recovery plant which we installed, and I regret to say it proved a failure, as the upkeep on the conveyor was so high that, after a little over a year's working, we scrapped the ash portion.

I now come to the point in the practical running of large gas engines, on which I am afraid very few of us will exactly agree—viz., to what extent the gas should be cleaned before it is sent to the engines. There is no doubt that gas engines must have clean gas delivered to their working cylinders in order to get the best work, and there is good reason to believe that the principal cause of the early troubles experienced in this country with engines working on bituminous producer gas were caused by the gas being insufficiently clean; but I am afraid there is a decided tendency at the present moment to exaggerate the degree of cleanliness required and the plant necessary to obtain it; in fact, prospective customers have in some cases abandoned the idea of gas engines owing to the rumours which they have heard regarding the expensive plant required to clean bituminous fuel-producer gas, and the space that it occupies. It is

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Mr. Stewart. quite unnecessary to have the gas in such a clean state as is often described when people say, "the very last traces of tar should be removed." I am perfectly certain that if cotton wool or any other absorbent was placed ½ in. from the petcock of the supply pipes of any of our engines for 10 minutes, it would become slightly discoloured; but we have found no detrimental effect either to output or upkeep. So long, therefore, as the gas is what might be called reasonably clean, there should be nothing to fear. The plant for obtaining this reasonable cleanliness is cheap and compact, and entirely automatic, requiring the minimum of attention, and the tar recovery will pay for itself in the shape of fuel for raising steam or as an additional by-product.

Regarding the cost of engine repairs, several speakers have questioned the authors' allowance for repairs to the gas plant and engines. Now, in our steel works in Scotland, the plate-rolling mill is driven by a 1,500-H.P. 2-cycle gas engine, and the auxiliary plant connected with the mill is all driven by electricity, generated by a 500-H.P. gas engine. This engine has had no standby, and has worked continuously for exactly two years now, night and day. The total number of hours' delay caused by mechanical or electrical stoppages has been under 40 hours, 9 hours of this time being directly due to mechanical breakdown; the remainder was electrical trouble. On the 1,500-H.P. engine, which has been working for a similar time, not an hour of rolling time has been lost. The repair bill for the 1,500-H.P. engine during twelve months' continuous use, from January 1 to December 31, 1908, including two half-yearly inspections, amounted to £119 9s. 5d. The repair bill on the 500-H.P. electrical generating set during the same twelve months, and inclusive of all the items previously mentioned for the 1,500-H.P. engine, was £91 10s. 6d. The figure of £15 per week, stated by Mr. Allen as being upkeep cost of his gas plant, is confirmed by our experience, and I think the authors considerably overestimated the total cost of repairs and overhaul.

With regard to the limit of size of a single-cylinder unit, Messrs. Andrews and Porter place this at 1,500 H.P., and another gentleman appears to fear trouble from any engine capable of giving a greater output than 1,000 H.P. As a matter of fact, we have experienced no greater trouble with a cylinder 43⅜ in. diameter on the 1,500-H.P. engine already referred to than with those of 24¼ in. diameter, which is the smallest cylinder we have made. This is, however, undoubtedly due to the exceptionally simple form of the cylinder and combustion chamber in the engines referred to. I therefore see no objection whatever to gas engines being manufactured in larger units than the maximum stated in the paper.

With regard to the fear that the acid present in the exhaust gases will quickly deteriorate the exhaust piping, the first gas engine was started in our works six years ago, and still has its original piping in almost as good condition as when it was put in, although water has been continuously sprayed on the exhaust to deaden the sound

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—our works being situated in a residential district. The introduction of exhaust-heated boilers aids most effectually in silencing, and it is no longer necessary to use a water spray. I think, therefore, there need be no fears in future in regard to the life of gas-engine exhaust piping. Mr. Stewart.

Several speakers have expressed disapproval of the figure given by the authors as the price of their fuel, but I think that this figure entirely depends on local conditions. At the present moment we are paying 7s. 1½d. per ton for fuel, delivered at our works, for our ammonia recovery gas plants, and our average yearly yield of sulphate of ammonia works out at 84 lbs. per ton of fuel. There is also, I think, a mistaken impression that for ammonia recovery gas plants one is very much tied down in the choice of fuel. This is not quite the case, as we have at our works ammonia recovery plants aggregating 100,000 H.P., and during the coal famine in the West of Scotland fifteen months ago these plants were compelled to work on almost any fuel that the pits were pleased to send us. Of course, the proportion of recoverable by-product was less, but otherwise the plant worked almost as easily as with a better grade of coal.

There is also an impression among engineers that while gas engines are being successfully operated on the Continent with blast furnace or coke oven gases, they are not so reliable when run on producer gas. When I state that in our experience we have built a total of 16,000 B.H.P. of engines in this country, which are now running solely on bituminous fuel producer gas, and range in power from 400 up to 2,000 B.H.P., this apprehension will be seen to be without foundation, and I should like to impress upon the meeting the fact that during the last six or seven years the makers of large gas engines in this country have been experimenting and gathering information which the Continental gas engine makers have had little opportunity of obtaining. The reason of this, of course, is that the conditions in this country and those in Germany are so entirely different. Nearly all the gas engines in Germany have been laid down in connection with large blast furnace works. In this country, however, gas engines have generally been laid down at steel works, very few of which have blast furnaces working in direct connection with them. It has, therefore, become essential to lay down a producer plant, and while all credit is due to German manufacturers for their early enterprise and experimental work with internal combustion engines, we in this country had not merely to pick up and continue the threads of Continental experience, but to face an entirely new problem, and we are now prepared to build as large gas engines as any we might see on the Continent.

Finally, in designing a gas-engine station the daily curve and not the average yearly curve should be taken into account for settling on the size of unit to be installed, and in this connection the question of utilising accumulators, either in the central station or in sub-stations, is worthy of careful examination. By taking the peak with accumulators, which will enable the gas plant to be run at its most economical load—

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Mr. Stewart. viz., 0·75 to full load—a considerable saving may be effected, as shown by Mr. Taylor.

Mr. Dixon. Mr. WALTER DIXON: In assuming a station of the power and working conditions decided upon, the authors have taken the only course possible for illustrating a basis of comparison. Had the power concerned been larger or smaller, or other basis conditions been taken, they would probably have been subjected to the same criticism, that the complete set of figures could not have been applied to any existing conditions.

The early days of gas engines have been mentioned, and some slight regret expressed that the development of large gas engines had not fallen to this country. But though credit may be due to Germany for the development, yet when the conditions which called for these large gas engines are considered, it reflects no discredit whatever upon British engineers that they have allowed the Germans to go forward. It must not be forgotten that it was first demonstrated in this country that a gas engine could be run, and electricity generated satisfactorily from blast furnace gases, and I remember with pleasure my association with the late Mr. B. H. Thwaite in the carrying out of this first experiment, the credit of which was entirely due to this country.

It is not only, however, in regard to gas engines that the authors' remarks are of importance, but also from the combination of producer gas plants with ammonia recovery. Whatever might be said as to the economy of working a gas-engine station with ordinary producers, the economical conditions become more pronounced when an ammonia recovery plant is embodied if suitable working conditions can be obtained. It is in the securing of such working bases and conditions that the co-operation of the station engineer and the makers of the machinery will attain the best results. Some of the speakers appear unfamiliar with the results obtainable in ammonia recovery plants. Outside the British Isles there are perhaps only three or four such ammonia recovery plants as are now under discussion, this type of plant being essentially a British development. Although until recently their advance has not been rapid, there have been erected and set to work in this country during the past few years producer gas plants of about 150,000 H.P., about five-sixths of which have been constructed by the Gas Power and By-Products Company, Ltd., of Glasgow, with which I am connected, and whose gas is not Mond gas. These plants were not primarily installed for the generation of power in gas engines. Notwithstanding this, I find, on looking into the matter, that engines aggregating a total of 9,800 H.P. are continually being run from these plants, and that the value of the by-products recovered from the coal used exceeded in all cases—sometimes by nearly 20 per cent.—the original cost of the coal gasified, and, under certain conditions, where the plant was of an economical size, and with a suitable load factor, it may be taken for granted by the station engineers in this country that a gas plant working with an ammonia recovery plant will pay the cost of its own fuel and this expense be eliminated.

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Mr. Dixon.

As to what proportion of load should be taken up by gas engines, with or without ammonia recovery plant, this has been discussed, and opposite opinions have been expressed. I have carefully considered the matter with the knowledge before me, and, in my opinion, the electric generating stations of the future will consist of gas engine and ammonia recovery plant to deal with the whole of the station constant load, which will be generated, so far as the fuel cost is concerned, for nothing. Whether the peak and other loads will be taken by accumulators, gas engines, or turbine plant, will depend on local conditions, such as relative capital expenditure, cost of available ground, size of station, cost and quality of coal, and relative economy of working. Each of these items has to be considered in turn, and may change the advantage from one type of plant to another.

Mr. Handcock.

Mr. H. W. HANDCOCK: While it is impossible to generalise as between steam and gas, I feel that the authors are fully justified in having brought this subject forward with so much confidence. There is one point on which they have not touched, probably because the paper relates entirely to large gas engines, and that is that, as the size of engine decreases, the capital cost per kilowatt remains much the same with gas, whereas with steam engines it increases. In these same circumstances also, the consumption per horse-power-hour does not very materially increase with a gas engine, although it does with a steam engine. To mention a figure arrived at in actual practice, we found that at one of our own stations, with an output of less than 150 k.w. on a purely lighting load giving a very bad load factor, the cost of fuel, using coke at an average price of 16s. per ton, is as low as 0·25d. per unit sent out, and the cost of oil and petty stores 0·036d. We shall have to go a long way before we find steam plant that can anywhere approach economy like that. Another point that may be emphasised with advantage is the very great value of gas power for industrial works which have long working hours in districts where fuel is fairly expensive. Taking, for argument's sake, a works with an output of 750 k.w., running 140 hours a week, 50 weeks to the year, with coal at 12s. a ton, and comparing average steam turbine figures with gas figures, we find that the total annual saving in favour of gas at the end of the year is something like £2,200, or £3 per kilowatt, which, translated into dividends to the shareholders, means a very respectable dividend on a capital of some £40,000. It therefore follows that there is every incentive, with long hours of running and fairly expensive fuel, to use gas power, provided it is fairly reliable, and that the cost of repairs is low. In that connection I would limit myself to a few main points, as time is short. In the first place, an engine should be underloaded rather than overloaded—*i.e.*, it should have a large reserve of power. The initial compression should not be overdone, especially if there is much hydrogen present. The scrubbers should be frequently cleaned, since the engine is intended to work as a gas engine and not to become a receptacle for tar. Producer gas practice should not be based on practice with blast furnace gas. The quality of the gas must be kept even. A

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Mr. Handcock. well-designed engine, if these rules are observed, will give reliable running with few repairs, and great economy, when coal is dear, as compared with steam.

Mr. Miaskowski. M. P. v. MIASKOWSKI (*communicated*): I have had during the last few years charge of about fifty large gas engines, ranging from 600 to 3,200 B.H.P., and I am in the possession of actual figures which my firm has gained from the experience of some of the 247 double-acting engines which were built or ordered during the last six years.

The authors remark that it is difficult to give an exact figure for the amount of costs for upkeep and repairs, as one plant may be good and give no trouble at all, while another plant may cause continual difficulties. I quite agree with this, but think it is only the result of more or less careful attendance. They also estimate that the total costs of repairs of the whole gas plant will not exceed £4,000. The costs of upkeep for the gas producer and ammonia plant are estimated at £500, those for the buildings and auxiliaries are very small—say £300—so that for the upkeep of the gas engines and alternators there remains £3,200. I think this figure is on the safe side, and it is quite possible that half the amount will not be exceeded with carefully attended modern gas engines. Taking, therefore, £1,600, the cost per unit would be 0·0183d. That this figure is safe enough I can prove to you by several reports, which my firm at Nuremberg has in hand, in which the average cost of repair of a number of gas-engine plants, all running at about the same load factor, amounts only to 0·00851d. per unit. The figure of £970 given for the oil consumption of the gas engines and alternators seems also a little high. According to our experience, 0·24 gallon per 1,000 B.H.P. an hour is ample, and includes the lubrication of compressors and water pumps. Taking this figure against 0·37 gallon given by the authors, the cost of oil would only be about £650.

Mr. Donkin. Mr. S. DONKIN (*communicated*): Referring to page 22 of Mr. Andrews' paper, a figure is used for banking boilers, which amounts to 11·2 lbs. of coal per hour per 1,000 lbs. per hour evaporative capacity of a boiler.

Some very complete tests were made to ascertain the amount of coal used for banking boilers by Sir Alexander Kennedy in the years 1894 and 1895, and the results then obtained show that 5·75 lbs. of coal per hour per 1,000 lbs. per hour evaporative capacity of the boiler is an outside figure for both small marine dry-back and small water-tube boilers where the grates were hand-fired and the coal used was Welsh. In other terms, this figure amounts to about 1 lb. per square foot of grate area per hour.

A few weeks ago a 16½-hour banking test was made for me on a large modern water-tube boiler having a maximum output of 30,000 lbs. of steam per hour, and fitted with chain-grate stokers and Miller furnaces. This test, in which care was taken to keep the pressure constant and at the working point throughout, gave a result amounting only to 2½ lbs. of coal per hour per 1,000 lbs. per hour evaporative capacity of the boiler, or about ¼ lb. of coal per square foot of grate area

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per hour. The coal used was Midland small, having about the same cost as the coal in the paper. As this result is obtained with modern plant, I consider the figures given on page 24 of the paper in calculating the total coal used per annum for banking are too high. The figure 3,330 tons in the paper should be 750 tons, and the lbs. of coal per unit generated reduced to 3·22, making the overall thermo-dynamic efficiency 8·17 per cent., which is not an unreasonable figure. Mr. Donkin.

Mr. ARTHUR H. LYMN (*communicated*): In the discussion upon this admirable paper it was referred to as the severest attack that had been made by gas power upon steam practice, and that this paper almost left one confused, and was stated to be almost convincing in its arguments. I welcome this assurance, feeling satisfied that if those interested in the generation of electrical power will go to the trouble of examining into facts and seeing for themselves what is being and has been done, they will have before them all that is necessary to complete the convincing process. Mr. Lymn.

We have heard at the meetings that producers are difficult to operate, but as a matter of actual fact it has been found considerably easier to operate a gas producer on rational principles than to fire a steam boiler. In making this remark I would lay stress upon "rational principles." It is generally known that with the old type of hot gas producer, where a depth of fuel of about 2 ft. was utilised, the variation in gas quality was very great, but one might as well compare the old balloon boiler with the modern water-tube boiler as compare old with modern gas-producer practice. I would undertake when operating a single gas producer that the quality of the gas produced should not vary more than 5 per cent. above or below the average, and this trifling variation, which would not affect the gas engine in any way, becomes infinitesimal in a battery of producers. I think I may safely state that no boiler can be fired in ordinary practice with such a degree of constancy.

It has been alleged that gas producers require a specially selected coal. Again this is ancient history, and to-day a good power gas producer can deal successfully with the coals from any locality in Great Britain—indeed, I might say in the whole world—and it is very rarely that a coal has to be rejected. It is quite certain that many coals which would be rejected by steam users can be operated satisfactorily in properly constructed power gas producers, and I think the authors of this paper are not only justified in taking the cost of coal at as high a figure for steam as for gas, but are unquestionably erring in favour of steam.

An eminent station engineer has remarked upon the number of small producers included in the authors' project. I would merely point out that each of those producers is equivalent to 2,000–2,500 H.P., and gas-plant makers are prepared to put down a plant as large as 100,000 k.w. and to give proper guarantees. Considerable stress has been laid upon the question of obtaining clean gas, but it should be noted that there have been many cases where gas engines have run for

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Mr. Lymn. six and even twelve months without a sign of tar being found on the valves—indeed, it is a well-known fact that in many localities town gas is dirtier than producer gas made in a properly designed plant. I would lay stress on the necessity for proper and careful design, and would warn all those interested in gas power against "freak" prices quoted by irresponsible makers who deliberately cheapen plant, and thus render it unsatisfactory, in order to get in with some municipality.

Among a number of station engineers there seems to be a general belief that the gas-producer plant is less developed than the gas engine. But my own experience has proved the contrary, and I can show these gentlemen at any time large plants of 10,000 H.P. and upwards which have not been stopped for an hour during five to ten years, and one large plant which gasifies and recovers ammonia from 200 tons of coal per day, and which has never been stopped during a period of fifteen years except for a short time in consequence of a fire in the works. I am sure that, having regard to these facts, we must accept the reliability of gas-producer plant as a *fait accompli*, and that the proof of the same thing as regards gas engines may well be left to the makers thereof.

The authors apparently object to a combined gas and steam station. It is obvious that under certain conditions of load a gas station is better than a combination; but for the average load conditions existing in most large central stations I am of opinion that an ammonia recovery gas plant installed to deal constantly with the bulk of the load, combined with a steam plant to take the peak, would be found to suit station engineers' convenience and views better than a station composed solely of gas power. In putting forward this aspect of the question I do not overlook the fact that the standby losses of a gas plant are very much smaller than those of a steam plant, that the separate units of gas plant can be started to work with greater ease than those of a steam plant, and that generally speaking they will work much more economically while in operation; but there is the important factor of increased capital outlay and consequently increased depreciation upon a plant which may only be carrying the peak (say 5 per cent.) of the maximum output of the station. I feel strongly that this is a matter upon which it is impossible to lay down hard and fast views, since the advisability of adopting such a combination must be specially considered for each case and must depend upon the local conditions existing.

Opinions are expressed from time to time that the repairs on a gas-producer plant are more costly than those on a steam boiler plant. Those who express these opinions are doubtless unaware that there are numerous cases of gas producers which have worked as long as three, four, and even five years continuously day and night, and on being stopped, emptied, and examined, have been found to require hardly any repairs, and have been restarted forthwith. I think I may safely challenge any steam users to find me a steam boiler with such records. Unfortunately it is always difficult for contractors to obtain working costs from private firms, but I am in a position to give you a few

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interesting figures as to repairs to gas-producing plants. On a 10,000-H.P. ammonia recovery plant of a now obsolete design, and which worked at full load continuously, the cost of repairs, oil, waste, stores, insurance, sundries, etc., was £1,149 during one whole year. On properly designed modern plants this figure is much reduced owing to the elimination of lead apparatus. The following shows the low repair costs of three non-ammonia recovery plants :— Mr. Lyma.

1. 2,000 H.P., four years, £146, or £36 10s. per annum.
2. 1,000 H.P., during 1908, £10.
3. 1,000 H.P., during 1908, £42.

The particular plants referred to are working intermittently on an annual load varying between 22 and 27 per cent. As regards depreciation, the authors have been taken to task. I have given above one example in which a plant has been working for fifteen years, has suffered the effects of a fire, and is probably still good for another fifteen years. Meanwhile, although one may look upon the last fifteen years as having been greatly devoted to pioneer work in this industry, the modifications which have been made in gas plant are not such as to render it really necessary to scrap any material portion of the plant.

A point of considerable importance in central-station design is the elasticity in choice of site. Mr. Allen drew attention to the great advantage possessed by gas power in the possibility of placing the gas plant at a distance from the gas engines, which is quite impossible in the case of steam plants. The same gentleman questioned the advisability of installing ammonia recovery for only a portion of the plant. In this case he has evidently overlooked the fact that an ammonia recovery plant not only pays best but also works best when operated at a reasonable load, say not less than 40 per cent. Though I am entirely in agreement with Mr. Allen's views upon gas plants generally, I cannot agree that an expert chemist is a necessity for the efficient operation of an ammonia recovery plant. All that is really required is a good tester with some chemical works experience at 30s. or £2 per week, but he need not be a trained chemist, and very excellent results are obtained where the plant is working under these circumstances. Such installations are simple and require no more expert supervision than a steam plant.

As regards the net result of sulphate of ammonia recovery, I would supplement the authors' remarks on page 16 by stating that as a general rule the amount of sulphate obtained from an ordinary coal is between 80 and 100 lbs. per ton, and its net value, after allowing for cost of sulphuric acid and all manufacturing expenses, varies between 0·8d. and 1d. per lb., according to the selling price of the sulphate and the cost of the acid. Accepting the figure of 90 lbs. at 0·8d. per lb., we find that the net saving per ton of fuel works out at 6s. Professor Threlfall took exception to the authors having accepted so large a return of sulphate of ammonia, on the ground that in his opinion there was only one district in this country where so much sulphate could be

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Mr. Lymn. obtained; but I could mention to him some ten plants working in different parts of this country whose average ammonia recovery throughout would be slightly more or less than 90 lbs. per ton of fuel gasified—indeed, two of these plants are producing as much as 100 lbs. A very pointed remark was made by another speaker to the effect that the recovery of sulphate of ammonia simply wiped out the coal bill. I fully endorse his remark for certain circumstances, and it is even possible to make a considerable profit on the sulphate of ammonia alone, irrespective of the gas produced; but at the same time I think a general statement of this kind is likely to do more harm than good, since it can only apply to those few cases where either fuel is cheap or the percentage of nitrogen contained in the coal is high. I notice that the authors refer to the heavy cost of sulphuric acid, but when we realise that this is only about 30s. per ton, and that the selling value of sulphate in this country is about £11 per ton, I do not think that the cost of acid can be looked upon as particularly high. They also refer to the lower efficiency in heat units of an ammonia recovery plant as against a non-recovery plant. Their remarks are perfectly correct, but the difference is not at all a serious one, the efficiencies being in the proportion of 14 to 15—a very trifling difference when we consider the immense advantage of ammonia recovery.

Ammoniacal effluent difficulties were mentioned by one gentleman as an objection to gas plant. I think this was intended to apply to lighting-gas works, but in gas-producer plants the process of recovering the ammonia from the gas is absolutely different from that employed in lighting-gas practice, and there is no ammoniacal effluent. The only impurity which can possibly be present in effluent liquors is an infinitesimal amount of light oil which comes from the tar. This, however, is simply a disinfectant and can do no harm, and in a well-designed plant it is quite unnecessary for even this liquor to be sent away from the plant, since the cooling water can be used continuously over and over again. It may be alleged that water containing a small amount of tar is not suitable for cooling in cooling towers; but this has been done in practice for many years, and is found to work well. As regards standby losses, the authors state on page 22 a guarantee figure of 50 lbs. per producer per hour. Over long periods it has been found that the standby losses per 1,000 H.P. in producers work out at approximately 14 lbs. per standing hour. It has been said that the Mond producer is very costly and complicated, but I think the charge is unfounded. It is quite impossible for a good power gas producer to be sold at other than a reasonable price, but yet it must be a thoroughly efficient and carefully designed piece of apparatus; and surely those who habitually use water-tube boilers cannot consider a Mond producer complicated in design, while it is certainly quite as easy for a workman to operate as a steam boiler. Again, a gas producer can be overloaded without causing difficulties, and generally without appreciable reduction in the ammonia yield; but it is true that certain fuels are more sensitive than others, and with these the rate of gasification for maximum ammonia

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recovery has a clearly defined limit which can be determined beforehand by gas-plant makers. It has been thought by some that the cheaper the coal the less advisable gas power becomes. This would seem to be the case on first considering the subject of ammonia recovery plants, but it is entirely a question of the amount of nitrogen contained in the coal. A plant is now being erected in Nottinghamshire by the Power Gas Corporation to recover ammonia from 150 tons of small coal per day. The coal is extremely cheap, and renders it possible to make a good profit out of the ammonia alone, while a great deal of the gas is absolutely wasted—*i.e.*, burned in the air—and this appears to be a very suitable and extremely economical case for gas power. Mr. Lymn.

Before closing I should like to draw attention to the important advances which have been made in the last few years in the industrial utilisation (by means of gas producers) of combustibles which were previously neglected. I would specially mention peat, which can now be very profitably gasified under ammonia recovery conditions; indeed, there are already three peat-fuel plants by the Power Gas Corporation either in operation or very nearly completed, one of them being for an electric distribution station in Italy. We all know that peat in its natural state contains an enormous amount of water; but there is no difficulty in drying it down to 50 to 60 per cent. moisture, in which condition it can be satisfactorily gasified. From numerous peat deposits as much as 150 to 200 lbs. of sulphate of ammonia may be recovered per theoretically dry ton of peat, while producing at the same time a perfectly satisfactory power gas. Such plants will yield a return of as much as 80 to 100 per cent. on the capital without considering the value of the gas.

Station engineers may look upon this phase of the gas-power industry as having little interest for them, but when they consider the possibility of large stations being erected at or near peat bogs, the current being transmitted therefrom to towns or used in works requiring cheap power, they will doubtless view the matter more seriously.

Dr. R. DRAWE (*communicated*): I have compared the author's estimate of running costs of a gas-engine installation given on page 30 of the paper with some actual results that I have recently obtained from a gas-driven installation generating 35,000,000 units per annum, from which I find that the author's estimate is on the high side. Dr. Drawe.

For instance, the actual cost of fuel, taking coal at 11s. per ton, works out at 0·0586d., say **0·060d.** against the author's **0·0775d.**

The actual cost of oil, waste, stores, water, and repairs works out to **0·072d.** against the author's **0·1035d.**

The actual cost of interest and depreciation, taken at 15 per cent. on the capital, works out at **0·123d.**, against the author's **0·202d.**

Finally, the actual total cost works out at **0·256d.**, against the author's **0·383d.**

At another large installation, working on coke-oven gas, and generating 40,000 **k.w.**, the depreciation and interest amount to **0·150d.**, and all other costs to **0·105d.** The total cost for 1 unit, therefore, **0·255d.**

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Dr Drawe.

The load factor of these two installations is about 65 per cent.

Our experience has been that there is no greater difficulty in running large gas engines on producer gas than on either blast-furnace or coke-oven gas. The producer-cleaning plant extracts all the tar, and on recently examining one of our engines that has been running for two years on Mond producers, we could find no trace of injury from the small amount of sulphur in the gas.

We realise that the gas producers have been brought to a much higher state of perfection in your country than in Germany, and German engineers are now endeavouring to embody English experience in their design.

I am very confident that a combination of English producers with gas engines built on German lines will prove a thoroughly reliable and economical installation.

Discussion at Dublin, February 11, 1909.

Mr. Sturgeon.

Mr. J. Sturgeon: This paper is a most important and valuable one, and will prove a useful handbook and aid to those who have to design electricity generating stations. The authors deal, apparently, only with town stations having low load factors, and where land is costly and water supply scarce and dear. Perhaps the authors' conclusions in favour of large gas-engine units are justified. I am more concerned in general supply schemes, where the load factors are high, and the generating station situated in some country place near a natural water supply, and where land is cheap and floor space ample. Under such conditions I consider 500-k.w. units quite large enough. There is really no difference in thermal efficiency between a 500 and a 1,000-k.w. gas engine, while taking the engine and alternator together there is an actual saving in the smaller unit, owing to its higher speed. I have in my hand an estimate from the makers of the Körting gas engine, as follows:—

One 750-B.H.P. twin-cylinder gas engine, 111 revs. per minute, with 15-ton flywheel—with one 3-phase alternator, 500 k.w., 10,000 volts, 50 cycles, complete with rope-driven exciter, £6,520; two of these sets costing £13,040.

One 1,500-B.H.P. twin-cylinder gas engine, 24-ton flywheel, with 1,000-k.w. alternator, same voltage, &c., speed 88 revs. per minute, price £13,300, or £260 more than the two smaller units for the same total output.

But there are other important savings in favour of the smaller unit, namely, in the foundations, housing, crane, and standby units. The flywheel may be taken as an index of the crane-power required, and the larger engine would therefore require a crane 60 per cent. more powerful than the smaller one, and also with a greater span, and the building would have to be higher. In the standby plant the saving would be very great indeed. I consider these advantages would

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greatly outweigh an extra cost in attendance and labour, which would amount to very little. Mr. Sturgeon.

The authors' estimates of working costs are based on coal slack at 12s. per ton.

According to the figures on page 25, the sulphate of ammonia works out at 90 lbs. to the ton of fuel. If peat fuel had been used, the authors would have been able to get much more than that, and about 1 cwt. to the ton would be a conservative estimate. At the low cost of peat and higher percentage of sulphate recovered, it would pay to keep the gas producer and recovery plant running continuously, and let the gas blow to waste when not in use for the engines. These, of course, are not the conditions assumed by the authors. In a general supply undertaking they would get very high load factors, especially for electro-chemical and electro-metallurgical processes. For instance, at the Castner-Kellner Works, the load factor is over 95 per cent., but even with a third of that load factor I believe it would pay to run the ammonia recovery plant continuously. I have only to add that I personally feel indebted to the authors for a mass of valuable information which will be of service to me in the work I am now engaged upon.

Mr. G. F. PILDITCH (Chairman): Can Mr. Sturgeon give any information as to the effect upon the selling price of the great increase in the amount of sulphate of ammonia put upon the market by reason of these schemes? Mr. Pilditch.

Mr. STURGEON: The suggestion is a very natural one, but the fact is just the reverse. When Dr. Mond first brought out his system, the price of sulphate of ammonia was only £7 per ton. It has steadily risen since, until in 1907 the average price for the year was £11 15s. 8d. Of course there are minor fluctuations, as in winter the output from gas works is greater at a time when the demand is less, but getting towards spring the demand is greater just when the supply begins to slacken off. The deposits of Chili saltpetre are said to be showing signs of exhaustion, and we may in the future have to depend entirely upon manufactured fertilisers. The world's demand for fertilisers is enormous, and sulphate of ammonia still holds its own, in spite of the competition of other artificial manures, such as calcium cyanamide, nitroline, etc. It will be a great many years before the output can so overtake the demand as to affect the price to any appreciable extent. Mr. Sturgeon.

Mr. G. M. HARRISS: My experience with large gas engines is chiefly with the 500-k.w. National set, which ran side by side with steam sets at the Irish International Exhibition. I remember that the exhibition authorities tried nearly every maker to get such an engine, but most of them would not touch anything like the size required. The engine was made and put down in a hurry. The first night it started it was put on full load, and no hitch whatever occurred. It was often overloaded, but ran right through the exhibition quite as well as the four steam sets. I have no hesitation in saying that, in my opinion, it Mr. Harriss.

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Mr. Harriss. will not be very long before gas engines entirely take the place of steam engines.

Mr. Sowter. Mr. W. J. SOWTER: I am rather disappointed with the authors' deductions, and consider a very much better case could be made out for gas engines. True, a saving of 45 per cent. is shown (with the aid of the ammonia recovery plant), but the question is, whether responsible engineers will consider such a saving sufficiently attainable to warrant their entering upon what is, so far as this country at any rate is concerned, a huge experiment. I object to the steam station being penalised to the extent of over £2,000 per annum for water supplying, seeing that no engineer would think of putting down a turbine station inland if a good supply of water could be got, even if there were other serious disadvantages. Will the authors tell me why steam-driven exciters are to be put down in the gas-driven station instead of the exciters being direct-coupled to their own alternators? I am surprised to hear that the capital cost of gas-engine plants per kilowatt is so much higher than steam. I recently got prices for 100- to 200-k.w. direct-coupled high-speed gas engines and dynamos, and came to the conclusion that the cost was almost exactly the same as an up-to-date steam station. I think that the authors could have made out a very much better case for the use of gas engines for small stations having capacities of only a few hundred kilowatts, as the coal consumption per unit with steam sets is high, while the small gas engines are practically as economical as the larger sizes.

Mr. Tomlinson. Mr. T. TOMLINSON: I am particularly pleased to notice the method by which the authors have arrived at the probable coal costs in the cases they have given, as in a recent communication to the Engineering and Scientific Association of Ireland I enunciated the same method. The value of the paper rests in the fact that the figures given do not merely represent results achieved at two different stations, where perhaps the conditions may be widely different, but are figures arrived at by an accurate process of deduction, and even if the totals are not strictly accurate, the comparisons between the two cases probably are. I do not quite see how the authors managed to get an overload capacity out of a gas engine, but, of course, it is all a matter of rating.

Mr. Stewart. Mr. P. H. STEWART: If large stations were started all over the country producing sulphate in such enormous quantities, the market price would fall and the price of sulphuric acid increase. With regard to steam turbines, I have had no trouble whatever with them, and have never known the blades to strip.

Mr. Tatlow. Mr. W. TATLOW: My experience is limited to gas engines of very moderate size, but I have found these on the whole very reliable and satisfactory. There can be no doubt that with the increasing cost of fuel, which is bound to make itself felt more and more as the coal-mines gradually become exhausted, the claims of the gas engine will force themselves on engineers; already in the case of large traction stations the cost of fuel is accountable for 80 per cent. of the total generating costs, and it seems as if the use of the internal combustion

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engine is the only means of obtaining a substantial reduction in fuel consumption. In view of the success obtained with oil engines using the Diesel cycle, I cannot understand why no attempt seems to be in progress to construct gas engines working on this cycle. In the matter of reliability it seems unreasonable to expect that a machine with reciprocating parts such as a gas engine can be as reliable as a machine, such as a steam turbine, having a simple rotary motion and an even turning moment. Mr. Tatlow.

Mr. A. T. KINSEY: It is instructive to be assured by an independent investigation of this kind that there are numbers of recovery plants where the sale of the by-products has almost equalled the cost of the fuel used. This points to cheaper power. In choosing the site for a large gas-driven station, the question of silencing the exhaust would appear to be a matter for careful consideration, judging from the difficulty of doing this even with small gas engines, so as to avoid complaint of nuisance. In the past water was looked to for cheap power. In an Irish city, with ample water power, current is charged at 5d. per unit. In a much smaller town, with a suction gas plant, the price is 3d. per unit, and there is no recovery plant. Both are private concerns. Mr. Kinsey.

Mr. G. F. PILDITCH (Chairman): It is evident from the figures which Mr. Andrews has placed before us that gas engines will, at any rate, run steam-driven plant very close in the future. Although the capital cost of gas plant is somewhat higher than steam plant of equal capacity, there seems little doubt that in many cases the cheaper running costs will more than balance the extra capital charges. Of course, each case has to be considered on its merits. I think that engineers in this country are perhaps a little nervous about large gas engines, and prefer to put in steam-driven plant on the score of reliability, even though the running costs are likely to be a trifle higher. Mr. Pilditch.

With reference to the estimated running costs on page 30, I am rather surprised to find the same figure given for repairs for both gas and steam-driven plant. I should have expected to find that gas plant cost more in repairs than steam plant; but at the same time, not having had any experience with large gas engines, I am not prepared to dispute the figure given by the authors. With this exception, I consider that the comparisons are very fair indeed.

In thanking the authors for their paper, which I consider a most valuable one, I feel that I am only voicing the sentiments of all members of the Local Section.

DISCUSSION AT MANCHESTER, FEBRUARY 16, 1909.

Mr. C. E. DOUGLAS: The comparison of the working costs and the comparison of the initial costs shown are likely to be severely criticised by many present. I had the privilege of preparing some figures on gas and steam plants which were put before this branch of the Institution two years ago, and I was severely heckled on that occasion. Personally, I am a great believer in the gas engine, both in its present state and as Mr. Douglas.

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Mr. Douglas.

regards its future. When you see stations such as those of which Mr. Porter has shown photographs, with 60,000 H.P. of gas engines in one installation, I think you will agree that there is considerable hope for the large internal combustion engine. Even as far back as four or five years ago there existed in America a power station of gas engines of the double-acting 2-cycle type aggregating 40,000 H.P. Whether the gas engine ever compares with the steam turbine for units of 3,000 to 5,000 k.w. and over, I am not prepared to say, but I have a great belief in their utility up to more modest powers of some 1,000 k.w. per unit. We have after all to bear in mind the fact that the turbine has a definite place for installations in large towns, where land is expensive and space an important consideration. On the other hand, perhaps space is not the only thing to bear in mind, and having regard to the development of high-tension transmission, it is a simple matter to put large generating stations a little further out, where land can be more readily obtained, provided, of course, that facilities obtain for a convenient supply of fuel. The necessity for a good supply of water is not nearly so great with the gas as with the steam station.

There is one point I have not clearly understood, and that is with regard to the amount of coal required to run the turbine or gas engines on no load. I take it that the figure which was given, and which was shown to be the same in either case, is the coal actually consumed when the machines are running round light. That figure, I think, is not of very great importance from the economical point of view, for, after all, you are not going to run your engines for more than a few minutes a day with no load. Just recently I have had occasion to go into the matter of coal consumption very closely for a steam turbine station, and it has been a difficult matter to arrive at the correct figure. I should have had less hesitation in fixing on a figure for a gas-engine plant. As a matter of fact, I think the figures that have been given by Messrs. Andrews and Porter are very fair averages indeed for the steam station, and also for the gas station. As already stated, I cannot say whether or not there is a field for the really large gas engine as compared with the large steam turbine. I believe there is, but I do not think that field will be opened to us just yet. If you compare the capital cost of the two installations referred to by the authors, we have to deal with very large units; but if you institute a comparison between smaller units and smaller installations, where units do not exceed 500 to 1,000 k.w., and the aggregate installation is reduced in proportion, my opinion is that the capital costs of the steam and gas installations are practically on a par. The larger you go in your units, the less appreciably expensive, I think, will your steam station be than your gas station, on account of the relatively small space occupied by steam turbines of large output and the relatively low cost of these machines for high powers.

I am not very sure about the discrepancy factor. Do I take it that this gives you, from the theoretical consumptions, the actual consumptions which have to be considered attainable? From my own expe-

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rience, I should not have thought a discrepancy factor of 25 per cent. was enough for the steam plant at any rate; but, after all, the figure has been carefully prepared, and it is possibly sufficient. With regard to interest and depreciation, I do not know what percentage municipal engineers consider fair and right, but looking at the matter from the standpoint of the Lancashire mill-owner and the Yorkshire woollen manufacturer, we do not find that they will let us off under 10 per cent., and not infrequently a higher figure still has to be allowed for. Mr. Douglas.

There is one point which has not been touched on in the paper though it is of importance; I mean the possibility of using a cheaper grade of fuel with the gas plant than with the steam plant. If you consider the question specially in reference to London, where expensive anthracite coal has frequently to be burned under steam boilers, either to abate or avoid smoke nuisance, it will be seen that a great reduction in total cost of coal can often be effected, and I believe there is considerable scope for gas-engine work there. Not only may there easily be a 50 per cent. reduction in the quantity of coal used, but since a low grade bituminous coal can be consumed, without smoke, in the closed producer plant, and a further saving in price effected as compared with the use of anthracite, the total monetary saving is considerable. This has been proved in several cases, and can be shown in many others.

I am glad to hear of the instances of parallel running cited by the authors. There has been an edifying correspondence in one of our electrical papers on the subject of gas engines and their application to electrical driving, and it is quite amusing to see the number of letters which have appeared regarding the impossibility of gas engines being used for driving alternators in parallel. Even single-acting 4-cycle gas engines have been so used for the last six or seven years, and now it is a matter of common occurrence; with double-acting 2-cycle engines the difficulty disappears altogether.

I am glad to be able to endorse the authors' statements as to examples of reliability, and am personally acquainted with several cases where large gas engines have been employed, running continuously day and night, in some cases including Sundays, for three months without a stop, and for eighteen months without so much as requiring internal examination or valve adjustment.

Mr. S. L. PEARCE: I have read this paper with extreme interest, looking at it from the point of view of a municipal engineer interested more especially in the question of large gas-engine units. I must confess at the outset that I am not able to seriously shake the figures that the authors have put forward this evening. The question really resolves itself into two factors. You have the heavier capital expenditure on the one hand, over against which you set the reduced fuel costs. These latter are of course dependent upon the price per ton, over which we have little control, and also on the load factor of the station. Those are the two determining factors in this question, but after carefully reading this paper I am inclined to Mr. Pearce.

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Mr. Pearce. think that Mr. Andrews' view, as expressed in *Electrical Engineering* in October, 1907, in which he advocated a combination of gas plants with steam plants, is a sounder view than the one he takes up to-day, in which he apparently goes the "whole hog," and plumps for gas plants at stations which have a very low load factor. We are all familiar with the disadvantages of gas plants, and I need not dwell on those, beyond briefly stating them to be (1) excessive weight; (2) inability to meet sudden overloads; and (3) the extra space taken up. It is no good dogmatising on these three points, each engineer must consider them in relation to his own local conditions. The station engineer, in considering the question of prime movers, will naturally have in view three points: firstly, reliability; secondly, capital outlay; and thirdly, fuel economy. Before we consider gas plants in detail, I think we have to make up our minds that the gas engine of to-day is a thoroughly satisfactory and reliable piece of mechanism. I, in common with many engineers in this country, through the courtesy of Mr. Andrews and other friends, have been able to see a good deal of large gas-engine plant at work on the Continent, and for my part I am quite prepared to admit that the large gas-engine unit to-day is as reliable as a large steam unit. With regard to the producer end, we have, unfortunately, very little experience. I use the words in a comparative sense, because on the Continent it is a question of blast-furnace gas or coke-oven gas, but at home there are one or two prominent examples of producer plant using bituminous coals, and we hear satisfactory reports of these. At the present time I think engineers who are considering the question of gas plants would like to have more information from the users, and to be actually satisfied in that the producer end is as reliable as the gas engine itself.

Dealing with the question of the size of unit, I said at the outset I was more especially interested in the size up to which the gas engine could now be built. Speaking as regards Manchester, I do not think we could consider putting in units of much less than 5,000-k.v.a. capacity. We have not too much space, and having installed steam units of 6,000-k.w. capacity, we could not drop very much below this output with advantage.

With regard to the capital costs on page 19, and the steam figures given therein, I would say that they appear to me to be generally too high. Knowing the prices at which large turbo-generating plants can be bought to-day, I think the total figure of £139,000 odd should be reduced some 10 per cent., and that of course would have some bearing on the table which is given later on. The capital costs for a gas plant using 5,000-k.v.a. units could probably be brought down to £15 per kilowatt.

Then you come to the important question of fuel economy, and here the authors state that various tests of gas engines of different outputs show a figure of 1 lb. per kilowatt-hour. That figure, however, does not appear to be borne out in practice, and I take it as referring

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to the actual units sent out on the feeders. It does not accord with the results given on Table III. of gas-plant efficiencies. In no single case do the examples cited come down to a figure of 1 lb. of fuel per unit generated. Furthermore, some figures were put before me some time ago by a firm of gas-engine builders, and although they were considering a set of conditions in which the size of unit was some 4,000 k.w., and the load factor at least 70 per cent., the guaranteed figure that they gave worked out to about 1¾ lbs., so that 1 lb. of coal per unit generated is, I think, rather too small when considering the set of conditions that the authors have taken in the first part of their paper. I would consider 1½ lbs. to be nearer the mark. There is not, in my opinion, more than 1 lb. per unit to be saved as between a gas and a steam station. Mr Pearce.

Then comes the question of the price you are going to receive for your by-products. The authors take that at £11 per ton, and at the present time that is very near the mark. I think the gas department of the Manchester Corporation for the last three contracts made have obtained £10 15s., but if the supply of these by-products should become extensive, the price may possibly fall. It does not seem to me that one ought to rely on maintaining the authors' price of £11 per ton if there is likely to be a very great supply of sulphate of ammonia in addition to other fertilisers, and I think one must adopt a very conservative estimate in considering this question of the sale of by-products.

The standby coal figures that the authors give on page 22 are a very important item on the steam side of the question, and they adopt a figure of 448 lbs. per hour per plant unit. It may be of interest to you to know that some seven or eight years ago, when I first came to Manchester, I set out and made some tests with a view to arriving at this figure on the city station's plant, and found it to be 5 lbs. of coal per day per kilowatt installed. If you take that figure and compare it with the authors', you will see they are almost identical.

On page 23 the authors give a set of curves, amongst which there is one for a 6,000-k.w. turbo-alternator at Stuart Street station. I may say, in reading this paper, I accepted the authors' figure for the no-load losses on the Manchester turbine. My attention has been drawn to the fact that the figure of 15,000 lbs. is not correct; the figure should really be 9,600. Of course that is against the steam-turbine side of the question, because if you decrease the no-load losses, you still have a total consumption of 95,000 lbs., and that means that the coal consumption per actual unit generated is higher. I think that is probably the reason why on page 24 the overall thermo-dynamic efficiency of 7·4 in steam plant is higher than the authors thought it should be, as given in Table III. on page 38. They have also, I think, taken a rather extravagant figure for the cooling water per hour, no less than 288,000 gallons, which works out at 70 times the weight of steam. Surely that is excessive.

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Mr. Pearce.

With regard to the question of maintenance and repairs, it is, of course, difficult to put up any figures for the repairs to gas plants. As Mr. Andrews explained, it is a point on which there is very little information forthcoming, and assuming his figure correct for gas, one would certainly regard the figure they have adopted for steam plant as being on the high side, and would be inclined to reduce it by 25 per cent. It would also be interesting to know why the authors on page 28 state that the repairs for generators would certainly be lower for gas-driven plant than for steam or turbine-driven. Our experience goes to show that the turbo-alternators are likely to cost far less in upkeep than reciprocating slow-speed sets. Regarding the question of depreciation and interest, of course in considering industrial concerns one has to take a fairly high figure for interest—something in the order of 5 per cent. Municipalities are able to get money cheaper, and therefore you can knock off something like 2 per cent. I think 10 per cent. is too high, and, on the other hand, 6¼ per cent. too low. I would suggest an equated figure of 8½ per cent. for gas and steam based on the lives of the separate parts of the installations.

Subject to these foregoing criticisms, the estimates for gas and steam would be amended to 0·423d. total costs per unit for the former and 0·483d. for the latter, still showing a substantial advantage to the former. The effect of fuel price and load factor is, of course, the whole gist of the question. Under the second set of conditions given in their paper the authors have, I think, set out to prove too much in taking the case of these low load factors of the order of 10 per cent., and proving that the gas plant is better even under those conditions. I have taken out a series of figures in detail, and with coal at 10s. per ton and a 10 per cent. load factor I arrive at a total cost per unit generated of 0·835d. per unit for gas as against 0·8d. for steam, so that it seems to me you are getting very near the dividing line, and it would be of interest to construct a series of curves on the lines of the criticisms offered and to show at what point as regards the load factor and fuel price it is economical to use gas or steam plants.

Mr. Stead.

Mr. W. Stead: I am in the fortunate position of having to deal with gas engines and steam turbines, both in manufacture and in operation. At the Westinghouse works we have about 1,200 B.H.P. of gas engines, and the remainder are reciprocating Corliss steam engines. If we have to shut down the gas engines owing to the gas being required for other purposes in the works we very soon feel it in the coal bill. Our two producers are Mond producers of 1,000-H.P. each, and have been at work now for about four years. In that time we have relined them at a cost of about £75 each, and that has been practically the only outlay. The other portion of the producer, the outside work, does not deteriorate in the same way as boiler work does. The only trouble in a producer job is that particular care has to be taken with the tar, and the producer people as a whole certainly underestimate the evil effects of tar. Recently a Liverpool firm has produced a burner for tar which can be used in connection with a

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boiler, 23 cwts. of tar taking the place of a ton of coal. With regard to the question of economy of gas engines, at one mill where a Westinghouse gas engine is installed they run at 1·2 lbs. of coal per brake-horse-power. The horse-power is about 750, and coal is 1s. 6d. per ton cheaper than that which would be used for a corresponding Lancashire boiler, which drives the weaving shed. I think all makers of gas- and steam-engine plants would very much like to be able to obtain the prices quoted by the authors at the present time. Mr. Stead.

Dr. F. H. Bowman: The first gas engine that I saw was about forty years ago, and it was very much ridiculed by engineers at that time, but from the diagrams shown to-night I think we may say that the gas engine has come to stay. The paper gives evidence of an enormous amount of research, and one thing that has struck me is the extreme fairness with which the authors have endeavoured to hold the balance between the steam and the gas engine. I quite agree that if fuel is very cheap, and there is a good supply of water in the neighbourhood, and the power used is very large, then the steam engine holds an equal chance with the gas engine. One gentleman said that the producer seemed to be the weak point in a gas station. I hold that the gas engine is not as perfect as the producer is to-day, especially the continuous action suction producer. With regard to the by-products that can be obtained from bituminous producers, if you go to an experienced chemist he will tell you that even if they could not be sold in the form mentioned there are other things with a much larger money value for which they could be utilised, but this is only applicable to large plant. The great advantage of the gas engine is that you obtain in smaller powers, say up to 1,000 H.P., a greater economy than you possibly can with a steam engine at a less cost, and for a very large number of the textile factories, as we know, the average quantity required is about 1,000 H.P. For powers up to 500 H.P. (and two 500-H.P. engines side by side will give you 1,000 H.P.) there is the suction producer, and I hold that if you put down a suction producer for, say, 500 H.P. the plant will cost less than £1 per horse-power, and there is absolutely nothing to get wrong if it is put down properly, and so far as I can judge now the continuous-action suction-gas plant is the best to use up to this power. When considering the question of fuel, in this case anthracite is undoubtedly the best, but it is dear. You can, however, use a portion of anthracite along with gas coke, which you can get almost anywhere. If the producer is properly designed to use coke and a mixture of anthracite you can use a cheap form of anthracite, and wherever a supply of that is available you can have a gas plant which, put down in 1,000-H.P. units, answers perfectly well even for stations which have to supply power and light to middle-size towns, and the cost in fuel will be about $\frac{1}{12}$d. per brake-horse-power-hour. In addition, you must bear in mind that for small units you get a greater economy in the same size units for gas plant than is possible with any similar sized steam plant. I quite agree with the authors' views regarding the "mixed" installation, gas-driven plant Dr. Bowman

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Dr. Bowman.

to take the smaller constant loads up to, say, 1,000 B.H.P. My own opinion with regard to bituminous plant is that it would not pay to put down a recovery process for less than about 4,000 H.P.

Mr. Watson.

Mr. S. J. WATSON: Before criticising some of the points that the authors put forward, I should like to say that as a result of a visit which I made last summer with Mr. Andrews and a party of engineers to inspect some of the large gas-engine installations in Germany, I came back quite convinced that as a practical piece of mechanism the large gas engine has arrived, and if any of you have any doubts in your mind on that point, you have only to run over and see some of these large engines at work, and you are bound to come back with the knowledge that the large gas engine is a thoroughly practical piece of apparatus. One of the places we visited there contained some 12 sets of engines, each of over 2,000 H.P., and I can assure you that the sight of that immense engine-room, 230 ft. long by 260 ft. wide, with these large sets running so quietly and well, was a novelty to us British engineers. You will not see anything of the kind in this country.

Coming to the figures given in the paper, the authors must have found some little difficulty in their endeavours to put the case fairly for the gas engine and for the steam turbine. They have, I think, tried to be quite safe in the figures put forward, but there are several points upon which I disagree with them. In the first place, it is unfortunate that they should estimate for a large turbine station with cooling towers. Such generating stations are, I think, more likely to be the exception than the rule. The capital cost of cooling towers and the revenue charge for water so considerably affects the total working expenses, that in fairness to the steam plant the authors should have based their calculations on the assumption that a natural supply of water was available. There is also one very important omission from both estimates, that is, the cost of the land on which the buildings for both types of plant are erected. I have taken the trouble to work out roughly the area of land occupied by each of these two buildings, and after doing so I came to the conclusion that one of the authors must have got out one set of plans and the other author the other set of plans, and on comparing them they found that unfortunately the turbine station only took up half the land that the gas plant did. Now what were they to do in order that this marked advantage to the turbine station should not be so apparent? And then a happy thought struck one of them. Put in cooling towers and a big reservoir alongside, and the two will come out about the same. The area of the land occupied has a very important bearing on the costs. If you only estimate a very low price for the land, it is obvious that there will be a considerable difference in the amount included for this item for the gas station as compared with the turbine station. I have carefully gone through the figures which Mr. Andrews gives for the cost of the steam plant of five 2,000-k.w. sets, on the assumption that you have an adequate water supply available, and I quite agree with the remark that Mr. Pearce made, that if you come to lay out a station of that size, you would undoubtedly be able

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to construct it at a very considerably less cost. In fact, I am quite sure that £117,500 would be sufficient to put down such a station to-day on very sound lines, working out at £11 15s. per kilowatt, including land, compared with the authors' figure of £13 9s., excluding land, whereas the gas plant including land would cost over £18 per kilowatt. Mr. Watson.

Now we come to the question of running costs, and the comparison of gas engines *v.* steam turbines is really one of increased capital *v.* increased fuel costs. The extra cost of the gas-engine plant, the interest, sinking fund, and depreciation will cost more, which will have to be saved on the fuel account in order to justify the expenditure. I have looked into the estimates of working expenses for the steam plant given by the authors, and consider they should be amended as follows, on the basis of a capital expenditure of £117,500 for a station possessing natural water facilities. The item of £2,550 for water would be eliminated. The quantity of coal allowed—viz., 3·55 lbs. per unit generated—is too high, and should be reduced to 3·00 lbs.; this is a figure shown by at least one undertaking on the list, and one, moreover, which will undoubtedly be attained by many others. It is also unfair to assume that the same class of fuel is required for both the gas and the steam station. If a price of 12s. per ton is taken for the gas plant, you may reasonably take a price of 10s. per ton for the steam plant. On these lines the working expenses for the steam plant, with 24 per cent. load factor, comes out slightly less than the gas plant, and if you reduce the load factor, the effect on the cost per unit owing to the reduced capital charges on the steam plant is much to the advantage of the steam station. I had made a note of the point which Mr. Pearce has also dealt with concerning a proposal put forward a short time back by Mr. Andrews, "that it would be advantageous to combine steam and gas plant for generating stations." The gas plant could then be used on that portion of the output having a high load factor, and the cheaper turbine plant used for peak loads, and this combination of the two types of plant should give very good results. One other point about the cost of working. One hears occasionally of men being gassed, and I do not know whether Mr. Andrews allows anything extra for insurance or compensation.

With regard to the question of overload capacity. A gas plant may only be overloaded 10 or 12 per cent., whereas a steam plant can easily be overloaded 33 per cent., and if you figure out the capital costs per kilowatt of maximum plant capacity, of course the steam plant will show up very much better than the gas plant.

Mr. V. A. H. McCowen: I have recently been considering a scheme very similar to the one the authors have put before us, and while I agree with some of their conclusions, there are a number of the figures with which I disagree. I think some of the assumptions on which the figures and conclusions are based are much too favourable to the gas-engine scheme. They start with the assumption of coal at 12s. per ton, which I consider is much too high a figure. If we neglect the cost of coal during the past year when prices were abnormally high, and take Mr. McCowen.

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Mr. McCowen.

an average over the preceding five years, the price comes out at something like 8s. per ton as a fair figure in the Lancashire district. This would reduce the authors' cost of fuel in the case of steam from £19,968 per annum to about £13,312 per annum, and in the case of gas from £12,280 per annum to £8,186 per annum, or a reduction in favour of the steam scheme of about £2,563 per annum, and this is for fuel alone.

Then there is the question of water. The authors include a system of cooling towers, which may be quite unnecessary, involving a much larger extra expenditure for steam than for gas. For instance, the cost of cooling plant for steam is given as £6,900 as against about £1,000 for gas. Even admitting that cooling towers are necessary, the charge of 6d. per thousand gallons of water is an excessive figure, and I submit that in this district it is quite possible to get it at one-sixth of the price from bore holes. This would reduce the cost of water in the case of the steam scheme from £2,550 per annum to about £425 per annum, and in the case of the gas scheme from £555 to £92 per annum, or a reduction in favour of steam of about £1,660 per annum.

With reference to the lay-out of the steam station, I consider the boiler units of 10,000 lbs. capacity each much too small, and see no reason why this size should not be doubled, and instead of having four boilers to each turbine, two boilers would suffice; this would reduce the capital outlay on the boilers, the standby losses, and the working expenses, and would also reduce the space necessary. With regard to what the authors call the "discrepancy factor," taking into account the very careful way they have estimated the standby losses, I think that the figure of 25 per cent. is much too high, and has the effect of increasing the coal costs of the steam scheme by a much larger amount than it does the gas scheme. For instance, this 25 per cent. discrepancy factor means an increase of 6,660 tons of coal per annum on the steam scheme, as against an increase of 4,093 tons per annum in the case of the gas scheme.

I should also like the authors to give us a little more information as to what they consider the minimum size of generating plant with which it would be advisable to apply recovery plant under the ordinary 24 per cent. load-factor conditions which they adopt in the paper. They suggest that "it is not worth while to recover sulphate of ammonia unless the output of the plant exceeds 2,000 H.P., and then only on an exceedingly good load factor." They evidently do not consider 24 per cent. as a good enough load factor for recovery purposes, except on a very large plant, and as this vitally affects the estimated fuel saving, it is a point on which further information would be most desirable.

The question of space necessary for the two schemes has not been given sufficient consideration. If the two plans given in the paper be compared, it will be noticed that there is a considerable amount of vacant space allocated to "cable stores, etc.," which is not part of a generating station. If we neglect this vacant space and measure the area of the steam scheme itself, it comes out to about 4,600 sq. yds., while the space taken by the gas scheme comes out to about 9,500 sq. yds.

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Mr. McCowen.

The space necessary for the steam scheme might, I consider, be reduced at least 25 per cent. by a rearrangement of the plant. This would reduce the area of the steam scheme to about 3,500 sq. yds., or very little more than one-third of the area of the gas scheme. This is a very important point where one has to pay a high price for land, and may materially affect the final economical results of the gas station as compared with the steam station. One might say, "Why not go outside the district and get cheap land?" It is, however, very often much cheaper to pay a big price for a site that is near the centre of gravity of supply than go further afield and even get land for nothing. The question of space is therefore, I contend, a very important one, and may in certain cases reverse the conclusions arrived at.

Mr. Seaton.

Mr. G. D. SEATON: I have seen big gas engines at work in numerous places in Germany, and there is no doubt that they are a success; but, as a Nuremberg man pointed out in Birmingham last week, they are all working with blast furnace gas, which he describes as the ideal gas for gas engines. If we could always have ideal conditions I think we should run through with turbines very much easier than we do. I am quite prepared to admit that the gas engine is a success, but I am not at all prepared to admit that the bituminous producer is a success. I think if the authors had any reliable figures about the working of big bituminous producer plants, they would have preferred to substitute them for the hypothetical figures they have had to rely upon. Mr. Emerson Dowson pointed out, in a recent letter to the *Electrical Times*, that although some bituminous producer plants were working satisfactorily, in many cases there has been serious trouble. Now there is probably no man in this room who knows more station engineers than I do, and it would be very difficult for me to say which man dislikes work the most, a genuine unemployable or a station engineer. Station men won't stand trouble. If there is the slightest trouble with plant, they are on the telephone to the contractor's man immediately. If they meet with serious difficulties they will exercise the rejection clause, and even with small ones they will make the life of the contractor's man a burden to him. The authors will no doubt eventually succeed in getting a big producer station to work, but I am afraid they will have a great deal more to put up with than I have, and I am rather inclined to think that they will find it to be unsatisfactory.

Mr. Atkinson.

Mr. J. ATKINSON: I would like to emphasise the statement in the last column of Table III., viz., that the average overall efficiency of the gas plants summarised is more than twice as great as the overall efficiency of the steam-engine or steam-turbine plants. This is a somewhat pregnant fact, but sounds no uncertain note. I would also like to call your attention to the last two paragraphs in the paper. Emphasising the fact that the standby losses are trivial compared to those in the steam plant, and also that the size of the station is a less disturbing feature in gas-engine plant than in steam-engine plant, I am led to question the statement on page 5, that when the load

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Mr. Atkinson.

factor is low it will generally be a mistake to use gas engines. It appears to me that the lower the load factor the greater the need for gas engines, the more so as it is easier to keep gas producers shut down than steam boilers. At the bottom of page 15 the authors speak of the difficulty of using gases containing a large percentage of hydrogen. This is quite correct, but my experience when working engines with different kinds of gas has been that dust has caused more trouble and difficulty than hydrogen. I am a little afraid that the authors are not cognisant of some of the most recent improvements in connection with producer plant. The latest development has been to eliminate one of the parts of the plant. On the diagram shown it will be seen that the gas passes by the brown line into the washer, then to the ammonia absorber, and then to the gas cooler. For some considerable time a plant of about 3,000 k.w. working with bituminous coal, at Crossley Brothers', Openshaw, has been running with a much simpler arrangement, in which the ammonia absorber and the washer have been combined in one part, omitting what is shown on the diagram as the ammonia absorber. This arrangement has been found to extract ammonia with quite as great an efficiency as a separate absorber, and it does away with one very expensive portion of the plant. There is also a reduction in the space occupied, and only one set of pumps is required. It will thus be seen that, so far as the improved producer and cleaning plant is concerned, there is practically no difference in the cost between a plant with ammonia recovery and one without, the same parts being required for both, and only the extra parts for evaporating the liquid and extracting the sulphate of ammonia being required in the former case. This being so, there would be no object in making a part of the plant suitable for extracting ammonia and a part not suitable, as in the plant described in the paper it would be desirable to extract the ammonia from the gas used during the peak load as well as during the lighter load. The elimination of the separate ammonia absorber shown in the plan would have a material effect upon the estimate of the capital outlay given on page 19, in which the difference of the four non-recovery producers with the necessary scrubbers, etc., is said to be £10,340, against ammonia recovery producers £18,490. Of course some of this latter figure includes the plants for evaporating and extracting the sulphate of ammonia; but a large proportion of the difference, some £8,000, would be saved, and this saving, combined with the profit on the ammonia from the whole of the coal burnt, would make the conditions more favourable to gas-engine plants.

I think the authors have favoured the steam plant on page 27, where they have estimated the number of attendants as three firemen and nine boiler-house men, against sixteen for the gas plant. I think the gas plant should be worked with a fewer number of men than the steam plant.

Mr. Fedden.

Mr. S. E. FEDDEN (*communicated*): I cannot agree with the authors on page 7 that it is much better to put down cooling towers and use

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town water, and I think that if I were confronted with that problem I should not put down turbines at all, but reciprocating engines. For a maximum of 8,000 k.w. I should not instal five 2,000-k.w. machines. I should prefer two 4,000/6,000 units and two 2,000/3,000 k.w. The cost of these four machines, including condensers, pumps, circulating pipes, etc., should not be more than £42,000 against the authors' price of £50,575, made up of the first three items on page 19, and under these conditions my steam and coal consumptions would be very much less than those given on page 22. My present coal consumption, with a much smaller load both as regards maximum demand and load factor, is considerably below 3 lbs. per unit generated, compared with the authors' figures of 3·55 lbs. The authors' proposal to put down twenty boilers of 10,000 lbs. capacity is, I consider, not good practice at the present day; the steam-consumption figure of 20 lbs. per kilowatt generated appears to me a fair estimate if it includes steam for all auxiliaries and steam-pipe losses. I should, however, propose to put down six boilers with a normal capacity of 30,000 lbs., each capable on emergency of steaming at least 50,000 lbs., similar to those I have had in use for the past four or five years, at a total cost, including economisers, chimneys, fans, foundations, etc., of £21,000, which is £10,000 cheaper than the authors' figure given on page 19; and, further, my figure includes the foundations, chimneys, and flues which the authors have included in the building item of £33,600. These six boilers would give you ample running capacity, with spares for repairs and cleaning, and by means of the larger units I should gain a still further economy in having less radiation, etc., than would be the case with twenty smaller boilers. On these two items alone, therefore, I could reduce the authors' capital expenditure estimate for steam plant by £20,000, and I believe if I had more time to go carefully into all the other items I could bring the total amount of £139,525 to something near £100,000 for the steam plant. I consider the cooling towers should be struck out altogether. The authors have made the standby banking losses for the gas plant exceedingly low as compared with the steam, and have also apparently made the cost of the cooling water for the steam apparatus balance that of the cold water required for cooling the cylinders of the gas engines and for use on the producers, which I think is hardly fair for the steam argument.

Mr. Fedden.

In conclusion, I think the crux of the whole question as to whether one should use gas or steam must be settled in each particular case by the price of coal and by the load factor on the plant, which must be a very big one if it is to equalise the heavy standing charges which would have to be met on the large capital expenditure for the gas plant, and also the heavy cost of labour of running the same. I note that the authors have thought it wise not to discuss the heavy maintenance of the gas engines as compared with the small amount of maintenance on steam turbines.

The AUTHORS (*in reply*): In the opening remarks of our paper we expressed the hope that the hypothetical estimates we were submitting

The Authors.

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The Authors.

for criticism would prove the means of attracting, as contributions to the discussion, evidence based upon actual working experience for and against the use of large gas engines. The results in this respect have far exceeded our most sanguine expectations. The pros and cons of the case have been so fairly and clearly brought out by the different speakers that we venture to think the discussion as a whole, which expresses the carefully considered and up-to-date opinions of so many engineers, will prove useful to all those responsible for the lay out of electric generating plant. As the majority of criticisms of our hypothesis have already been dealt with and replied to by other speakers, it would involve useless repetition on our part to go over the same ground again. We propose therefore to depart from the more usual practice of replying individually to each speaker, and instead to endeavour to summarise and classify the remarks under subject matter headings, and will incidentally endeavour to reply to those criticisms that have not been dealt with by other speakers.

General.—We gather that every speaker agrees that the question of using large gas engines should at least be considered in practically every future extension of power generating plant. The point upon which a difference of opinion exists is as to what are the conditions under which the acknowledged advantages of gas engines more than counterbalance their admitted disadvantages. This is a point which can only be determined by the engineer of each individual scheme after a careful study of the local conditions of the case in the light of such information as has been brought out in the discussion, or as may be available from other sources.

Capital Charges.—The principal criticism of our estimates has been centred upon the relative charges we assumed for initial outlay upon, and erection of, plant. Messrs. Addenbrooke, Chattock, Fedden, Robinson, Woodhouse, and Watson consider that we have unduly favoured the gas plant by estimating the capital charges of steam plant too highly. On the other hand, Messrs. Allen, Stewart, and Schmer consider the gas engine estimates equally high. It appears therefore that our estimates may have been too high for both, but that they were relatively correct. Mr. Pearce's opinion that the cost of the steam plant might be reduced to £12 12s. per kilowatt, and the gas plant to £15 per kilowatt is of great value, as we believe he has recently obtained actual tenders for both systems. In the amended statement we have prepared of the comparative costs of generating 21,000,000 units per annum by steam and gas respectively we have adopted Mr. Pearce's figures for capital charges. We think that instead of attempting to arrive at a definite conclusion as to the cost of either steam or gas plant, which must necessarily vary with each condition, it will be wiser to endeavour to determine what is the approximate difference in cost. Our own view is that this difference may be taken as being from £2 10s. to £3 per kilowatt in favour of steam turbines, though this is a somewhat greater difference than Mr. Pearce gives.

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Cost of Site.—Mr. Watson complains that the cost of land was not included in our estimate of capital charges. We endeavoured to include a figure for this, but found the cost varied so enormously, according to locality, that we concluded it was better to leave this item out of both estimates. Mr. McCowen considers that space for cable stores, etc., should not have been included in either scheme, and expresses the opinion that the space occupied by the steam plant might have been appreciably reduced. Mr. Stewart, on the other hand, points out that the area occupied by the producer plant might also have been greatly reduced. We agree that by crowding the respective plants into the smallest possible space and ignoring all yard space, cable stores, etc., it might be possible to do with some 4,000 sq. yds. less for the steam plant than for the gas plant. We think, however, that in the majority of positions in which an electric power plant would be installed, the annual charges upon this extra land would certainly not exceed 1s. per square yard, or, say, £200 per annum. We have included this item in our amended comparative statement.

Cooling Tower Site.—Messrs. Fedden, McCowen, Woodhouse, and Watson criticise our action in assuming that cooling towers would be used for condensing purposes. We are still of opinion, however, that a cooling tower scheme is the fairest standard with which to make comparisons. We might have quoted actual costs of water-side plants where the local conditions would have entirely favoured either gas plant or steam plant, but we considered that to have done so would have been absolutely misleading, and it would have been impossible, without full knowledge of the local conditions, to have applied these figures to other local conditions. On the other hand, the cooling tower figures are applicable to all schemes, and any engineer will be able to amend the estimate to suit his local conditions by cutting out the item of cooling towers and inserting his own figure for the cost of obtaining condensing water. We fear that those who have criticised our estimates in this respect have jumped to the conclusion that we have aimed at proving that gas engines are more economical than steam turbines for all purposes, whereas our intention was to merely put forward estimates which, after possible amendments in discussion, might be accepted as standard for certain given conditions, and which were at the same time, with slight modifications, applicable to other conditions.

Size of Units.—Messrs. Fedden, McCowen, and Woodhouse object to our assumption that twenty 10,000-lb. boilers would be used for the steam plant instead of a smaller number of larger capacity. Our reason for taking this size of boiler unit in the first instance was that we happened to have particulars before us of the actual cost of a boiler installation of this size, and we consequently showed this arrangement in the general lay-out plan. We afterwards obtained particulars of costs of other installations in which much larger boilers had been used, the total cost of which plant, with foundations, erection, and buildings, was approximately the same. We do not think that the size of boilers materially affects the results arrived at. Mr. Fox suggests that a more

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economical arrangement of the steam turbine plant would have been four 2,500-k.w. turbines instead of five 2,000-k.w. sets. This would have involved their being built for an overload capacity of 60 per cent. for two hours, with the result that the cost of generators would have been so much greater that we think no economy would have been effected. Mr. Chattock considers that our overload figure of only 33 per cent. is too high for the same reason. Messrs. Dowson, Douglas, Sturgeon, and Sowter think a better case could have been made for small gas engine units. On the other hand, Mr. Pearce considers there is a demand for larger units than any that have yet been built. In this connection Mr. Sehmer's remarks respecting the 8,000-H.P. engines now being designed by his firm and Mr. Allen's information respecting the possible 8,000-H.P. Korting engines, coupled with Mr. Booth's remarks *re* the limitations of sizes of cylinders and Mr. Stewart's assurance that there is no great difficulty in increasing the output, are interesting. Mr. Fox considers that the fact that "a small gas engine will work almost as economically as a large gas engine" is against the adoption of large engines, by which we presume he infers that large gas engines in public supply undertakings will be unable to compete with small suction plants on consumers' premises. We would point out, however, that the large installation has the great advantage of the possibility of effecting a considerable saving by recovering sulphate of ammonia, coupled with the fact that repairs and maintenance charges will be very much lower on the large plant, and finally that labour charges will also be much lower, as one engine-driver can control a 2,000-H.P. engine, whereas it is impossible to do with less than one man for a 50-H.P. engine.

Overload Capacity.—Messrs. Fox and Watson refer to the advantage of the high overload capacity of a steam turbine as compared with the 10 per cent. overload capacity of a gas engine. Mr. Sehmer affirms, however, that gas engines can be worked up to at least 20 per cent. overload. It appears to us that this question of overload is entirely a matter of rating, and we cannot understand why some standard rating should not be fixed, depending, as Mr. Chattock suggests, upon the overload capacity of the generator for a period of two hours. If, for instance, this overload capacity is fixed at 25 per cent., then a gas engine or steam turbine for a nominal 1,000-k.w. set must be capable of generating 1,250 k.w. for two hours, and 1,000 k.w. continuously. If all prime movers were rated upon this common basis, the question of relatively greater or smaller overload capacity would not then arise. Mr. Woodhouse expresses the opinion that the overload capacity of producers is somewhat limited. On the other hand, we have Mr. Humphrey's and Mr. Lymn's views, based upon working experience with producers, to the effect that their overload capacity is practically unlimited. The fact that the yield of ammonia is somewhat reduced during the period the producers are being forced is no serious drawback, as it is only in cases of emergency that forcing becomes necessary.

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Combined Steam and Gas Plant.—Messrs. Dixon, Highfield, Lymn, Pearce, Robinson, and Watson all advocate the combination of steam turbines and gas engines for dealing with the average load factors public supply undertakings usually have to contend with. One object we had in view in constructing the curves embodied in Figs. 13 and 14 was to show that for low load factors and cheap fuel a combined gas and steam plant would prove more economical than either steam plant or gas plant alone. We were disappointed to find that the results did not work out as we had anticipated. We are, however, inclined to agree with Mr. Highfield that the majority of central station engineers will, in the first instance, use gas engines in combination with steam plant, retaining the latter for the peak load, and using gas engines for the flat portion of the curve.

Producers.—Messrs. Addenbrooke, Woodhouse, and Seaton anticipate that troubles may be experienced with producers. On the other hand, Messrs. Allen, Lymn, Sehmer, Stewart, and Dr. Drawe quote experiences which show that there is little or no foundation for these fears. Dr. Bowman would prefer to use a large number of 500-H.P. suction producers rather than the comparatively small number of pressure producers proposed. We cannot help thinking that the working costs of handling a large number of small producers would be appreciably greater than of a comparatively small number of large producers.

Sulphate of Ammonia Recovery.—Professor Threlfall considers that our estimate for ammonia recovery is too high for general use. On the other hand, Mr. Lymn states that 80 to 100 lbs. per ton of coal is being obtained in widely different parts of the country. Mr. Allen estimates 95 lbs. of ammonia per ton of suitable coal, and Mr. Stewart quotes a yield of 84 lbs. per ton of coal costing 7s. 1½d. delivered at works. As Professor Threlfall points out, the amount of ammonia recoverable must necessarily depend upon the composition of the coal, and Mr. Addenbrooke makes the valuable suggestion that producer makers should prepare a list showing the amount of ammonia recoverable from leading classes of coal. To take a conservative estimate we have assumed a yield of only 85 lbs. per ton in our amended comparative statement. Mr. Pearce and Mr. P. H. Stewart doubt whether the price of £11 per ton will be maintained should the supply of this by-product become extensive. On the other hand, Dr. Bowman is confident that there will be an increasing demand for by-products from bituminous producers, and Mr. Sturgeon quotes some interesting figures showing that the price of sulphate of ammonia has steadily risen since the time when Dr. Mond introduced his system of recovering this by-product. The price upon which we based our estimate is considerably below that obtained last year. Mr. Lymn refers to an interesting plant that is being erected in Nottinghamshire solely for the purpose of recovering ammonia from coal, the bulk of the gas generated being absolutely wasted. Mr. McCowen asks what is the minimum size of a generating station in which it would be commercial

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to recover sulphate of ammonia, and Dr. Bowman puts the minimum limit at 4,000 H.P. We would add that it is quite as much a question of load factor as of size of plant. We are of opinion that with a high load factor it would pay to provide for ammonia recovery even if the maximum output did not exceed 2,000 k.w. It is entirely a question of the yield of ammonia being sufficiently great to cover the higher capital charges and higher labour charges on the recovery plant, which can only be determined for each specific case. Mr. Dixon contends that in a large plant, working at a high load factor, the sale of ammonia may amount to as much as the cost of fuel, and Mr. Lymn expresses the saving as being equivalent to 6s. per ton of coal gasified. Mr. Highfield, referring to Mr. Allen's results, quotes a return of 7s. per ton of coal. Both Mr. Allen and Mr. Atkinson express the opinion that the whole of the producer plant should be equipped for ammonia recovery. We think, however, that they have not taken into consideration the saving in capital outlay that can be effected by combined recovery and non-recovery plant. We are of opinion that the difference in yield of ammonia effected by using entire recovery plant would be insufficient to cover the additional capital and working charges.

Auxiliary Plant.—Professor Threlfall considers that there is some danger of placing too much reliance upon raising the steam required for auxiliaries and producers by exhaust heated boilers, whereas Mr. Allen recommends that all the auxiliaries should be steam driven, and expresses the opinion that the bulk of this steam will be raised by the exhaust boilers. We agree with Professor Threlfall that for an ordinary public supply load it is necessary to have a very considerable standby to the exhaust heated boilers in the shape of coal-fired boilers. This is particularly the case where plants are liable to be run for considerable periods on light load, or where the engines are frequently started and stopped. We assumed in our estimates, however, that these boilers would be largely fired with the tar residue from the producers, and we are very interested to note from Mr. Stead's experience that this is being largely done at the Westinghouse works. Mr. Stewart also confirms the value of the tar by-product for this purpose. In reply to Mr. Sowter's question as to why we have provided for steam-driven exciters instead of exciters coupled directly to the alternators, we would point out that a considerable quantity of steam is required in the producers which need only be at atmospheric pressure, and the exhaust steam from the exciting plants serves admirably for this purpose after it has done its work in driving the exciters.

Reliability.—Mr. Pearce's expression of opinion that gas engine units may now be considered to be as reliable as large steam units is very gratifying, but he, in common with Mr. Watson, who also admits the reliability of the gas engine end, queries whether the producer end is equally reliable. Messrs. Allen, Humphrey, Stead, and Lymn give evidence which should convince sceptics that the gas producer is an equally reliable piece of apparatus. Mr. Highfield

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considers that gas engine designers are still feeling their way. This appears to be a somewhat curious statement to make, taking into consideration that published returns show that the aggregate output of large gas engines of capacities exceeding 1,000 H.P. each, running and in course of construction, at the end of last year was considerably over 1,000,000 H.P.* Messrs. Allen, Handcock, Harris, and Tatlow all give evidence, based on actual experience, in support of the reliability of large gas engines. The Authors.

Parallel Running.—Mr. Humphrey's crank effort and angular velocity curves are most interesting, and should prove extremely useful, not only to gas engine and generator makers, but also to consulting engineers. The greater variation in cyclic regularity on full load for a given flywheel effect with quantative governing as compared with qualitive governing is clearly shown in Fig. B. We think, however, that the weights of the reciprocating parts which Mr. Humphrey has assumed for Fig. B are somewhat greater than is usual in modern European design, the result being that at lighter loads the cyclic irregularity tends to increase, so that a larger flywheel effect would have to be employed. By the use, however, of the more moderate inertia forces set out in curves g and h, the irregularity decreases at lighter loads, which is a point of some importance. The curves in Fig. C, where these smaller inertia forces are premised, correspond very approximately with data we have received from gas engine makers, and upon which we based our curves. His statement that the governing should not be too close to secure satisfactory parallel running confirms our own experience. Mr. Chattock's testimony as to the satisfactory parallel running he observed in Continental gas-driven stations is the more gratifying in that we have seen more perfect parallel running with reciprocating engines in Mr. Chattock's station than we believe is obtainable with the majority of turbine-driven plants.

British v. Foreign-made Engines.—Mr. Robinson and Mr. Stewart complain that English gas engine builders have not been fairly dealt with as compared with foreign builders. We regret that this question has been raised, as we carefully avoided all reference to any particular make of engine and endeavoured to confine our paper to the broad question of the scope for large gas engines. Since it has been raised we must say that we agree with Messrs. Humphrey, Dowson, Booth, and Dixon that a visit to the Continent is necessary to see the best practice in large gas engine work. We do not doubt that in course of time equally satisfactory engines will be obtainable in this country. In fact, one of the objects we had in view in preparing our paper was to induce English manufacturers to take an interest in the question. We endeavoured to obtain particulars of large gas engine installations from all possible sources in this country, on the Continent, and in America, and the information received was made use of without any discrimination as to nationality. Some makers in this country who

* *Zeitschrift des Vereines Deutscher Ingenieure*, vol. 52, pp. 2018–2019, 1908.

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claim to have made numbers of large gas engines intimated that they were unable to help us. Messrs. Mather & Platt and the Westinghouse Company sent us photographs of installations they had carried out, from which we had slides made and exhibited. They also, in common with Messrs. Crossleys, kindly furnished us with particulars of working costs, which we made use of in preparing the paper. Amongst others, we wrote to Mr. Robinson asking him if he could give us some photographs, etc., of installations carried out by his firm, but as we received no reply we concluded he was not able to do so. We have since learned from him that our letter was incorrectly addressed, and that it did not reach him. We are afraid that we did omit to ask Messrs. Beardmores for photographs of their engines.

Thermo-dynamic Efficiencies.—The high overall efficiency of a gas engine and producer combination as compared with a steam turbine and boiler installation appears to be universally admitted. Mr. Woodhouse complains that Table III., giving the overall efficiencies of a number of existing steam and gas installations, does not include his own results. The reason of this, as stated in our paper, is that inquiries were only sent to steam stations having an output exceeding 7½ million units per annum, and we gathered from the published returns that Mr. Woodhouse's output did not exceed that limit. We have added to the table results since received from one of the large power companies, also the London County Council results given in Mr. Rider's recent paper. Mr. Chattock objects to the arithmetical average given of the steam plant and gas plant efficiencies in Table III., and considers that a mean result would have more fairly represented the relative efficiencies. In preparing this table we found that dividing the total units generated at all the steam stations and all the gas stations respectively into the total quantity of fuel consumed (corrected according to its calorific value) gave a mean overall thermo-efficiency of 7 per cent. for the steam plants and 14·89 per cent. for the gas plants—that is to say, the comparison was more favourable to gas than the arithmetical average quoted. We consequently decided to show the result least favourable to gas. Messrs. Handcock, Stead, Kinsey, and Dr. Drawe all quote interesting experiences of economies effected by using gas engines. Mr. Watson and Mr. Fedden suggest that the comparison with steam turbines should be based upon the assumption that the fuel consumption of steam plants will be nearer 3 lbs. per unit generated than the figure we have taken of 3·55 lbs. per unit. We have not yet heard of such a low consumption under actual working conditions averaged over a period of 12 months for a plant maintaining its supply for 24 hours per day, and having a station load factor of less than 30 per cent. We have, however, taken Messrs. Watson's and Fedden's figure of 3 lbs. per unit in our amended comparative statement, as we admit that such a figure is within the limits of possibility.

Standby Losses.—Mr. Donkin criticises our allowance for banking boilers, and quotes results of some tests made by Sir Alexander

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Kennedy showing a much smaller fuel consumption for banking. On the other hand, Mr. Pearce and Mr. Dowson confirm our figures, the former from the result of records taken under actual working conditions. Mr. Lymn gives results of producer standby losses, obtained under actual working conditions over a long period, of less than one-half the figure upon which we based our estimate. We are gratified that Mr. Taylor and Mr. Addenhrooke approve of our attempted adaptation of Willans' Law as a means of ascertaining the generating plant no-load losses. We certainly think that closer attention should be paid to the fuel expended in an average generating station in meeting these losses. It is the general custom to refer to the comparative fuel or steam consumption of both steam engines and gas engines on full load only, whereas the no-load losses are really of equal importance. Fig. 10 shows that the no-load losses of gas engines and auxiliaries are slightly greater than the no-load steam turbine losses (without boiler banking and standby losses). It is evident, therefore, that the more fully loaded gas engines can be run the greater the gain in economy will be. Mr. Douglas suggests that the no-load losses are of no great importance from an economical point of view, as gas engines are never run for more than a few minutes per day on no load. He apparently has not appreciated the fundamental principle of Willans' Law, which is that if the no-load and full-load consumption of a generating plant are known the approximate consumption for any intermediate load can be readily determined. We fear that Mr. Pearce has misunderstood our figure of 1 lb. of coal per unit generated (estimated fuel consumption for gas plant, page 25). This figure applies to the extra or make-up units. For instance, a 2,000-k.w. gas plant fully loaded will consume, say, 3,000 lbs. of coal per hour or 1·5 lbs. per unit. The same plant generating 500 k.w. will consume 1,500 lbs. per hour or 3 lbs. per unit. It follows, therefore, that the fuel expended in generating the extra or make-up units will be $3{,}000 - 1{,}500 = 1{,}500$ lbs. for the 1,500 units, or 1 lb. per unit. Mr. Atkinson questions our conclusion that it is a mistake to use gas engines on a low load factor if cheap fuel is obtainable, as he contends that it is on low load factors that the elimination of heavy boiler standby losses becomes more pronounced if gas engines are used. The point we wished to make was that although the fuel consumption of a gas plant will be much lower than that of a steam plant, even on a low load factor, the capital charges will be so much higher that the saving on the fuel bill will in such cases often be insufficient to cover the extra interest and depreciation charges.

Cost of Fuel.—Mr. Woodhouse and Mr. Watson suggest that a cheaper coal can be used for raising steam than would be required for use in producers. On the other hand, Messrs. Sehmer, Lymn, Douglas, and Stewart give experiences of the use of a lower grade coal in producers than would be considered satisfactory for use under boilers. In connection with this Mr. Sturgeon's remarks *re* the use of peat with accompanying high ammonia recovery are interesting. Mr. McCowen

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suggests that the comparison should have been made with coal costing 8s. per ton, but he apparently overlooks the fact that in London a good steam coal usually costs more than 12s. per ton, and the average cost throughout the country would certainly be much more than the figure of 8s. he suggests.

Batteries combined with Gas Engines.—We have been very interested in the remarks of Mr. Taylor and Mr. Stewart respecting the use of batteries for dealing with the peak load, thereby reducing the capital outlay on generating plant and feeders and improving the load factor. Any development that achieves these objects must materially forward the large gas engine movement. The inefficiency of the batteries, which used to be considered an insurmountable objection to this proposition in connection with steam plants, practically disappears now that prime movers can be obtained consuming not more than 1 lb. of coal per "make-up" unit generated. We are unable to entirely follow Mr. Taylor's reasoning as to the saving in fuel effected, but we agree that by adopting his principle it is possible to save at least 1,600 tons of coal per annum upon the hypothetical scheme on which our fuel for gas plant was based. We have taken advantage of this suggestion in the amended comparative statement submitted. Another advantage incidental to the principle is that whereas the total fuel consumed is about 10 per cent. less, the sulphate of ammonia recovered will be greater because the whole of the producer plant will be "recovery" and not half "non-recovery" as in our original proposal.

Gas-fired Boilers.—Mr. Woodhouse and Mr. Addenbrooke raise the question as to the advisability of putting down ammonia recovery producers to generate gas to be burned under boilers. In reference to this suggestion, we would refer to Mr. Bryan Donkin's book on "Gas and Oil Engines," on page 242 of which the following appears: "The same quantity of gas will give 1 H.P. when used to heat a steam boiler for a fairly good steam engine, and 5 H.P. when fired direct in a gas engine cylinder." Whilst better results can doubtless now be obtained with steam plant than at the time the above was written, we are still of opinion that gas used for raising steam for the most economical steam engine that has yet been introduced would give less than one-third of the power obtainable from the gas used in an internal combustion engine. We also think that the capital outlay on producers, boilers, and steam engines would amount to more than that of producers and gas engines alone. Finally, repairs and other working expenses would undoubtedly be heavier for the gas-steam scheme than for gas alone.

Repairs.—Messrs. Woodhouse, Fox, and Pilditch express the opinion that repairs to gas plant will be higher than steam plant repairs, and Mr. Pearce considers our estimate for steam plant repairs 25 per cent. too high. Mr. Chattock, after inspecting a number of German gas-driven installations, anticipates that the repairs to gas engines will not be appreciably greater than repairs to steam plant, though he thinks producer repairs may be heavier. Professor Threlfall also criticises

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our estimate for producer repairs, but Messrs. Allen, Stead, and Lymn give results which confirm our estimate. Mr. Miaskowski gives results of a number of recorded repairs costs of several actual gas installations which appear to point to our estimate being much too high, and Mr. Sehmer offers to guarantee that the total cost of repairs of a 10,000-k.w. installation will not exceed £2,500 per annum, as against our estimate of £4,000. Mr. Stewart and Mr. Robinson also give some particulars of actual gas plant repairs which justify our estimate. Our own conclusions are that it would be safe to put the total cost of repairs of either steam plant or gas plant at £3,000 per annum, and we have taken this figure in our amended estimate.

Oil.—Mr. Stewart and Mr. Miaskowski both consider our estimated oil consumption for gas plant too high. We admit that our figure was in excess of working results given us by several users of large gas plants, but as our policy throughout has been to endeavour slightly to under-estimate steam costs and over-estimate gas costs, we have still retained our original figure in the amended estimate. Mr. Handcock also gives the actual cost of oil and stores of a 150-k.w. gas-driven set.

Cost of Water.—Messrs. Chattock, McCowen, Pearce, Sowter, Woodhouse, and Watson all consider that our estimate for make-up water is too high. We can only say that this estimate was based upon figures given us by makers of condensing plant of the quantity of circulating water required to maintain a 27-in. vacuum, and it was assumed that 3 per cent. of the water circulated would be evaporated partly as steam and partly by natural evaporation. The rate of 6d. per 1,000 gallons was based upon a rate Mr. McCowen himself had given us a few months earlier in connection with an inquiry for gas engines. We agree, however, that in the majority of cases it would be possible to drive a well and pump the water required at an inclusive charge of, say, 2d. per 1,000, and in our amended estimate we have reduced the water charge to one-third of that given in our original estimate. Replying to Mr. Chattock's inquiry, the item for water includes the make-up water for boilers as well as the make-up cooling water.

Interest and Depreciation.—Mr. Allen expresses the opinion that the depreciation of gas plant should be no greater than that of steam plant. Mr. Douglas considers 10 per cent. a correct amount to allow for interest and depreciation, but Mr. Fox and Mr. Woodhouse advocate a higher figure, presumably for both gas and steam plant. Mr. Pearce suggests an equated figure of 8½ per cent. for both gas and steam, which we note corresponds very closely with the average interest and sinking fund, or interest and depreciation, set aside by the various municipal and electric company undertakings in this country who publish their returns. We have, therefore, adopted Mr. Pearce's figure in our amended estimate.

Labour.—Mr. Fox considers our labour estimate for gas plant too low. On the other hand, Mr. Atkinson thinks our estimate too high. Mr. Allen suggests the employment of an expert chemist to obtain the best ammonia recovery results, but Mr. Lymn contends that a good

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tester, with some chemical works experience, at 30s. or £2 per week is all that would be required. Mr. Highfield considers one of the greatest drawbacks to the use of large gas engines in this country to be the difficulty of obtaining workmen experienced in the handling of such plant and of getting engineers who have any knowledge of internal combustion engines. This same objection was cited when steam turbines were first introduced. Surely it will not be suggested that such trifling difficulties as these will seriously retard the introduction of an improvement which will, if it is not first superseded by some other invention, ultimately effect a saving in the consumption of many millions of tons of coal per annum.

An amended comparative statement of total running costs of generating 21,000,000 units per annum with 24 per cent. load factor, revised in deference to opinions expressed in the discussion, is shown here :—

	Gas.	Steam.
	£	£
Total cost of coal at 12s. per ton... ..	11,320	16,750
Less sale of sulphate of ammonia ...	5,870	—
Net cost of coal	£5,450	£16,750
Oil, waste, and stores	1,345	438
Water	185	850
Labour	3,180	2,590
Repairs	3,000	3,000
Extra ground rent	200	—
Interest and depreciation at 8¼ per cent.	12,750	10,700
	£26,110	£34,328
Total cost per unit	0·299d.	0·393d.

Cost of generating power by steam under conditions specified = 31·5 per cent. greater than the cost of generating by gas.

The President.

The PRESIDENT: It is now my very pleasant duty to propose a hearty vote of thanks to the authors for their paper.

The resolution of thanks was carried by acclamation.

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Proceedings of the Four Hundred and Eighty-ninth Ordinary General Meeting of the Institution of Electrical Engineers, held in the Rooms of the Institution of Civil Engineers, Great George Street, Westminster, on Thursday evening, February 25, 1909—Mr. W. M. MORDEY, President, in the chair.

The minutes of the Ordinary General Meeting, held on February 11, 1909, were taken as read, and confirmed.

The list of candidates for election into the Institution was taken as read, and it was ordered that it should be suspended in the Library.

The following list of transfers was announced as having been approved by the Council :—

TRANSFERS.

From the class of Associate Members to that of Members :—

Ernest William Dean.	William C. Martin.
William Henry Heaton.	Frank J. Robins.

From the class of Associates to that of Members :—

P. P. Wheelwright.

From the class of Students to that of Associate Members :—

Ashford V. Clarke.	Richard W. Gregory.
Geo. Guy Ewer.	Percy H. Harding.
Samuel K. Ferrier.	Eric M. Hayward.
Henry Firth.	Gurth Johnson.
Joseph Goodman.	R. J. Kaula.

Thomas F. Lee.

Messrs. L. T. Healy and E. M. Sellon were appointed scrutineers of the ballot for the election of new members, and, at the end of the meeting, the following were declared to have been duly elected :—

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ELECTIONS.

As Associate Members.

John Holiday Adamson.
Hugo Aldum.
William Kennedy - Laurie Dickson.
Alfred Dover.
George John MacDonald.
James Ernest MacEwan.
Archibald Page.
Charles Thomas Peacock.
John William O. Sandell.
Ernest Edward Sharp.
John Shaw.

As Associate.

Arthur David C. Parsons.

As Students.

Adam Charles E. Anthony.
Rex Thomas Challoner.
William Gibson Covell.
Norman Benjamin Deane.
William Anderson Douglas.
Clarence Reginald Ford.
Frank Theodor Gerstenberg.
Andrew Thomas Gilbride.
Percival Grice.
Walter John Hannah.
Leonard Victor Hart.
Andrew Henderson.
Eric Rodney Hillman.
Daniel Jackson.
Stanley Johnson.
John Herbert Jones.
William Pitcairn Kemp.
Ernest Walter Knott.
Basil Widenham Leak.
Douglas Harold Linsley.
Henry James Loughlin.
William Mark.
Frank Percy Matthews.
Alan Gordon Mitchell.
Frank Oglesby.
William Parry.
Leonard Stanley Payne.
Stanley Herbert Pook.
Henry Roberts.
Gesner Sharples.
Wallis Sherley-Price.
Alfred Smellie.
George Caswell Smith.
Wei Shan Tcha.
Robert Thomson.
Edward Falkland Turner.
Thomas Henry Varcoe.

Donations to the *Library* were announced as having been received since the last meeting from Sir J. W. Barry, K.C.B., Messrs. A. Constable & Co., Ltd., U. Crudeli, A. E. Kennelly, M. Solomon; to the *Building Fund* from A. A. Crawford, Professor J. Epstein, J. R. Gillman, H. D. Symons; and to the *Benevolent Fund* from R. J. Wallis-Jones, to whom the thanks of the meeting were duly accorded.

The discussion (see page 51) on Messrs. Andrews and Porter's paper, "The Use of Large Gas Engines for Generating Electric Power," was concluded.

The meeting adjourned at 9.40 p.m.

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Proceedings of the Four Hundred and Ninetieth Ordinary General Meeting of the Institution of Electrical Engineers, held in the Rooms of the Institution of Civil Engineers, Great George Street, Westminster, on Thursday evening, March 11, 1909—Mr. W. M. MORDEY, President, in the chair.

The minutes of the Ordinary General Meeting held on February 25, 1909, were taken as read, and confirmed.

The list of candidates for election into the Institution was taken as read, and it was ordered that it should be suspended in the Library.

The following list of transfers was announced as having been approved by the Council :—

TRANSFERS.

From the class of Associate Members to that of Members :—

Charles Furness. | William McLellan.
Wm. Henry F. Murdoch.

From the class of Associates to that of Associate Members :—

Frederick Jas. Hughes. | Norman Wells.
Geo. Scovell Whitmore.

From the class of Students to that of Associate Members :—

Norman Cressy Bridge.
Geo. Stratton Cross.
John Dobson.
Chas. Marriott Dowse.
Wm. Gordon Guns.
Wm. Ernest Hean.
Clive Bredall Hobson.
Randall Garfield Hosking.
John Ernest Malcolm McGregor.
Geo. G. Mallinson.
Frederic Auber Menzies.
Douglas Wm. Munton.
Alan Faraday C. Pollard.
Wm. Ernest Poole.
Samuel Ernest Povey.
Frederick Pritchard.
Thos. Nixon Riley.
Grout Benjamin D. C. Saw.
Harold Thorpe.
Hildred Edward Webb-Bowen.
Richard Westbrook.
Henry Wilkinson.
Wm. Sydney Wright.
Arthur Zoller.

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Messrs. E. J. Farrow and C. W. Fourniss were appointed scrutineers of the ballot for the election of new members, and, at the end of the meeting, the following were declared to have been duly elected :—

ELECTIONS.

As Member.

Henry James Shedlock Heather.

As Associate Members.

Arthur Henry Atkins.
John Robert Bradley.
Arthur Crawford.
William Henry Duffett.
Henry Shoolbred Fox.
Arthur Leslie Hargrave.
Henry Anderson Hiorns.
Charles Stanley Mallett.
William Middleton.
Herbert John Mills.

Walter Thomas John Woodcock.

As Associate.

George Hugh Cutbush.

As Students.

Albert Bannister.
George Charles Alex. Chignell.
Herman Richard Constantine.
Harold Vincent Chandos Cotton.
Geoffrey Ambrose Houghton.
Frank Jackson.
Edward Jonas.
Edward Leslie S. Minors.
Francis Leonard Pedley.
Harry Milne Schofield.
Oliver Thornycroft.
Frederick Tyrrell.

Arthur Welch.

Donations to the *Library* were announced as having been received since the last meeting from A. G. Bell, A. P. Haslam, W. H. Patchell, L. H. Walter; to the *Building Fund* from H. C. Channon, A. Eden, J. C. M. Matthews; and to the *Benevolent Fund* from S. E. Britton, J. Gilligan, J. R. P. Lunn, S. Sharp, J. H. Woolliscroft, to whom the thanks of the meeting were duly accorded.

A paper (see page 113) by Mr. E. A. Watson, B.Sc., entitled "The Dielectric Strength of Compressed Air," was read and discussed.

The meeting adjourned at 9.45 p.m.

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THE DIELECTRIC STRENGTH OF COMPRESSED AIR.

By E. A. WATSON, B.Sc.Eng., Student.

(*Received December* 1, 1908, *and read in London on March* 11, 1909.

CONTENTS.

Scope of investigation.
Discussion of the best form of electrodes to be used for the determination.
The corona: Theory of its formation; relation of theory to actual results.
Description of experiments carried out, comprising alternating and direct-current tests.
Difficulties experienced with high-tension condensers.
Results of measurements made, showing the effect of shape of electrodes on the sparking voltage.
Values of the dielectric strength of air at various pressures deduced from the measurements.

The Dielectric Strength of Compressed Air.—The following experiments were made by the author with the object of determining as accurately as possible the manner in which the dielectric strength of air changes when it is compressed to pressures higher than atmospheric, chiefly with a view to its employment for the insulation of certain classes of high-tension apparatus for which oil or other insulation is not suitable.

Although the statement is generally found that "the dielectric strength of air is proportional to its pressure," yet actual measurements are very scanty and incomplete, covering either only low voltages or else only small increases of pressure above that of the atmosphere. The measurements made were therefore designed to carry the air pressure up to 200 lbs. per square inch (say 15 atmospheres), and to such a voltage that the readings obtained should truly represent the dielectric strength of the air itself, and should not be complicated by effects having their origin at the surface of the electrodes.

Electrodes Used.—For obtaining the dielectric strength of the air spherical electrodes were employed. These have the advantage that the maximum dielectric stress is calculable when the voltage, distance apart, and diameter of the sphere are known. In a paper by Dr. Russell on the "Dielectric Strength of Insulating Materials"* the following formula is given:—

$$R = \frac{v}{x} f$$

* *Journal, Institution of Electrical Engineers*, vol. 40, part 187, p. 6.

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where R is the dielectric stress at the surface of the sphere, v the potential difference between them, x their distance apart, and f a function of $\frac{x}{a}$, a being the radius of the spheres employed.

The values of f for different values of $\frac{x}{a}$ are given by him in the paper above referred to, and have been used in this work for deriving the true dielectric stress from the observed breakdown voltage.

Of course, if electrodes could be used consisting of large planes, there would be no need for thus deriving the dielectric strength, as the dielectric strength would then simply reduce to the ratio of breakdown voltage to distance apart, but in practice this is not possible as the edges of the planes would afford a region of maximum stress in which all the sparking would take place.

Points also, although adopted by the American Institution of Electrical Engineers as a standard form of gap, are not to be recommended, as the point is always surrounded by a body of disrupted air of uncertain shape and dimensions.

Dr. Russell has shown theoretically in the case of a spherical electrode that if $x < 2a$ disruptive discharge will ensue as soon as the maximum dielectric stress at the surface of the spheres reaches the dielectric strength of the air; that is to say that if $x < 2a\frac{dR}{da}$ is positive, whereas if $x > 2a\frac{dR}{da}$ is negative, and the first effect which occurs if the dielectric stress exceeds the dielectric strength is not as before a disruptive discharge, but is to cause a zone of disrupted air to form around the sphere increasing its virtual radius so as to diminish R and reach a stable condition. As V increases the radius of this zone grows larger, until a point is reached where $\frac{dR}{da}$ passing through zero reaches a positive value. When this occurs discharge will take place. This theoretical result is supported by consideration of any batch of spark-length voltage curves for spherical electrodes.

If we take any such series, and choose some distance apart of the centres of the spheres, we can from the curves determine the breakdown voltage for any sphere placed on those centres. This will generally be found to have a maximum value when the distance apart of the spheres is approximately equal to their diameter—*i.e.*, when $x = 2a$.

Hence we should expect that as soon as the distance apart of the spheres exceeded their diameter, a corona or zone of disrupted air would form before actual disruption took place, and the relation between the voltage and gap length would change.

The following reasoning will show that when conditions are such that a corona is formed before the actual discharge occurs, the curve connecting spark length and voltage should be a straight line.

Consider a spark-gap formed of two spheres of diameter less than

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the distance apart—*i.e.*, consider the case when $x > 2a$. Suppose the voltage is gradually raised. At a certain definite point the layer of air adjacent to the electrode breaks down. As, however, $\frac{dR}{da}$ is negative, this breakdown has the effect of diminishing the maximum stress so that there is no actual discharge. This is the point at which the corona begins to form. As the voltage is raised the size of the corona increases until a point is reached for which $\frac{dR}{da}$ becomes zero. For any further increase in corona diameter $\frac{dR}{da}$ would be positive, hence we have reached a point at which any expansion of the corona would increase the maximum dielectric stress, the condition of affairs becomes unstable and disruptive discharge takes place ; the diameter of corona for which the value of $\frac{dR}{da}$ becomes zero always bearing the same ratio to the length of the gap.

Hence whatever the gap length, provided it is sufficient for a corona to form, the actual disruptive discharge will take place not from the surface of the electrode itself, but from the boundary of a corona whose diameter is a fixed proportion of the distance apart of the centres of the spheres. Hence a large gap is but a magnification of a small one, and the voltage required to break it down will also be magnified in the same proportion.

It was actually found, however, that although if the voltage was sufficiently high a corona could be obtained, and that when this was the case the shape of the curve changed ; yet this did not take place until the distance between the electrodes was many times greater than that given by the theory.

This is well shown in Fig. 1, in which are given the curves obtained for spheres of radii 1·27 cm. (0·5 in.), 0·3175 cm. (0·125 in.), and 0·1588 cm. (0·0625 in.) respectively, and also for needle-points. It will be noted that :—

(*a*) The needle-point curve is a straight line. This could be predicted by exactly similar reasoning to that given above for the case of a sphere enveloped by a corona. In fact, it is the limiting case of this when the sphere becomes very small.

(*b*) The curves for the three different sized spheres all start off with the same initial slope, and are for the first part of their course very nearly straight lines. They soon begin, however, to droop away from this line, the ones of smallest diameter drooping the most.

(*c*) The curve for the smallest spheres after cutting the needle-point line turns up again, and appears as if it were running towards the needle-point line as an asymptote. (It was not possible to carry the voltage any higher, for reasons to be afterwards described.)

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(*d*) The curve has a point of inflexion approximately at the point where it cuts the needle-point line.

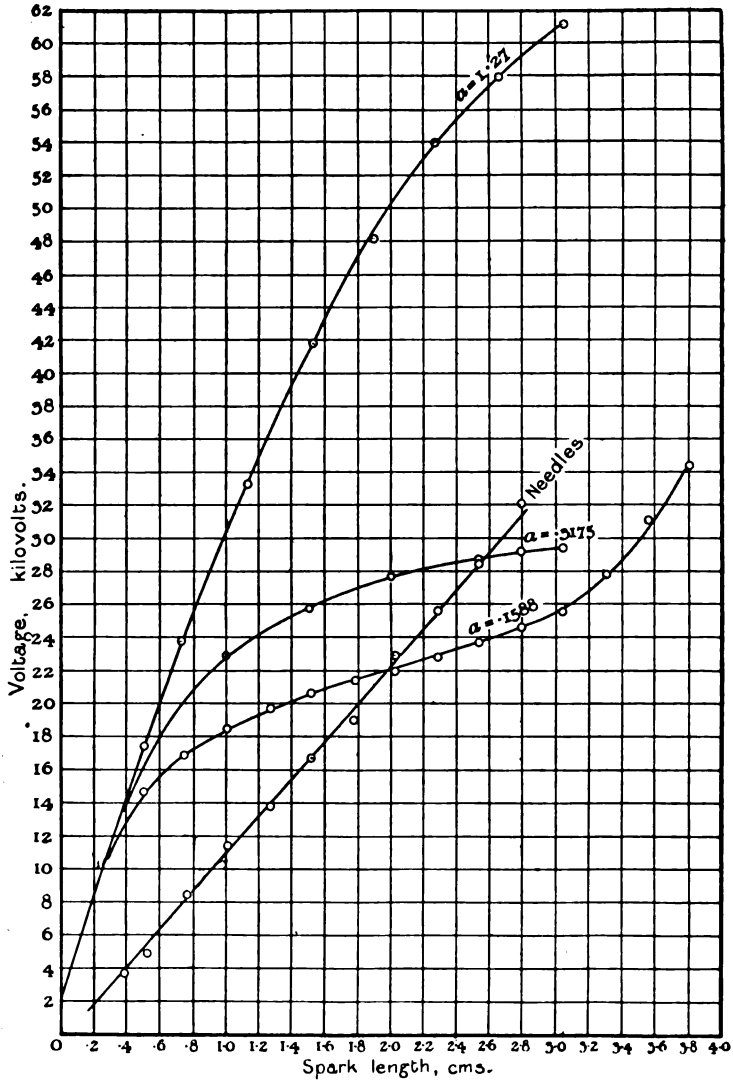

FIG. 1.—Showing effect of Electrode Shape on Breakdown Voltage.

(*e*) The curve for the next largest spheres also cuts the needle-point line, and it is probable that if the voltage could have been carried higher it, too, would have turned up again.

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(*f*) Experimental limitations rendered it impossible to carry the curve for the largest electrodes to the same relative stage as the other two, but it can be seen that it was bending so as to eventually cut the needle-point line.

It was, moreover, observed during the experiments that the first visible appearance of a corona coincided with the point at which the curve commenced to turn up again, and occurred at or about the point where it cut the needle-point line.

To a certain extent these results are in accordance with theory. For example, the turning up predicted by the theoretical consideration. It is, however, to be noted that if we assume the corona surrounding the needle-points to be circular in shape then the curves for the spheres should not cut the needle-point line. If the curves for the spheres were shifted to the right by an amount equal

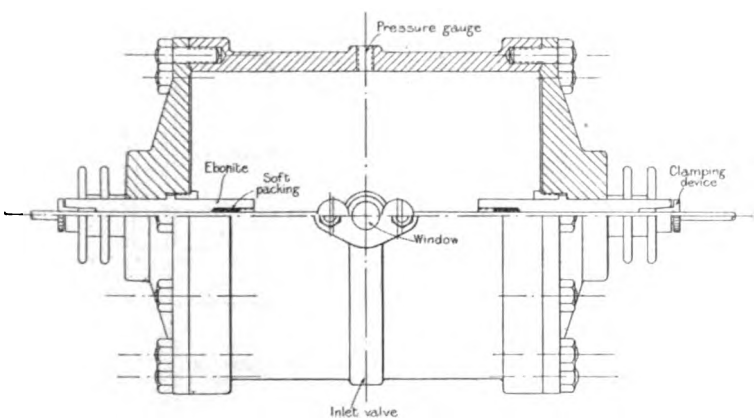

FIG. 2.—Arrangement of Spark-gap.

to the diameter of spheres employed, then the straight line to which the curve eventually tends should coincide with the needle-point line.

The chief discrepancy, however, lies in the fact that the gap at which the corona was first observed, and for which the curve first showed signs of turning up, instead of being equal to the diameter of the spheres employed, was in the case of the smallest spheres about six times as great.

It is difficult to explain why this should be so. It appears to point to the possibility that the layers of air near the surface of the electrode have a greater dielectric strength than the main body. At all events, this is a possible explanation. It has been found by various experimenters that, except for sparks of microscopic length, the metal of which the electrodes are composed has no influence on the breakdown volts, so that the explanation can hardly be sought here.

With this exception the results of the experiments agreed very fairly

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indeed with theory. This was especially the case with the values of the maximum dielectric stress as deduced from the breakdown voltage, with the aid of Russell's formula, the results rarely differing from the mean value by more than 1 per cent., and then only in an irregular way, evidently due to errors of measurement, provided that the gap was not too small.

With these introductory remarks on the question of the electrodes we will now describe the method of measurement adopted.

Two sets of measurements were made, with alternating-current

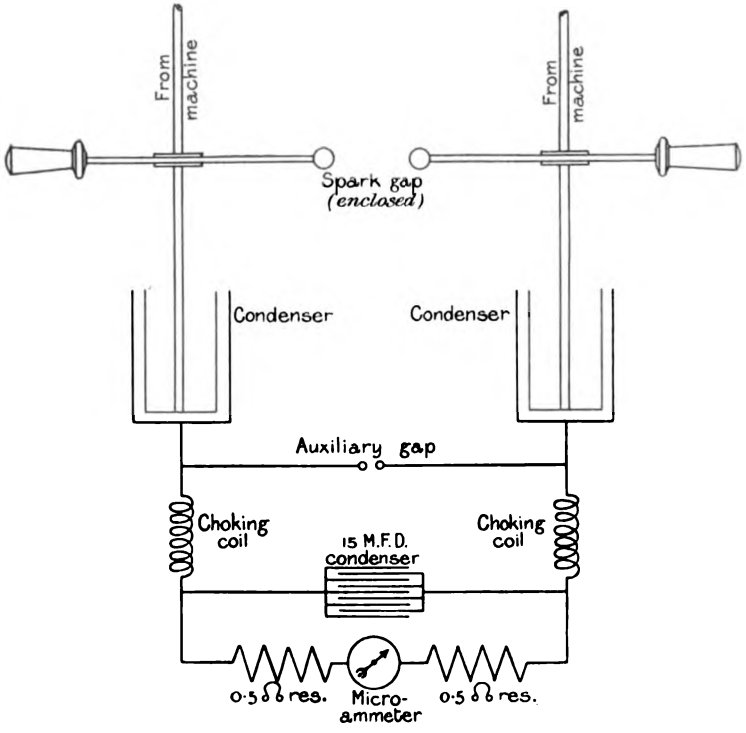

FIG. 3.

pressures derived from a step-up transformer and with direct-current ones from an influence machine.

In both sets the same spark-gap was employed, a scale drawing of which is shown in Fig. 2. It simply consisted of a cast-iron case fitted with removable ends, and equipped with observation windows and fittings for pressure gauge and inlet valve. The pressure could be raised to 200 lbs. per square inch without unduly stressing any part. The electrodes were mounted on rods carried through ebonite bushings in the ends of the case, and kept tight by small glands with soft pack-

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ing inside the bushing. As the amount of movement required was slight, elaborate packing was not needed. The distance apart of the electrodes was obtained by means of readings with an inside micrometer between points on the end of the bushing and a collar on the rod. Two points at opposite ends of a diameter were employed in order to detect and allow for any bending of the rod.

In order to tell when the electrodes were in contact a telephone and single Le Clanché cell were employed. By this means one could set them with care to within $\frac{2}{10000}$ in.—that is to say, successive settings to zero, if carefully done, agreed to within this amount.

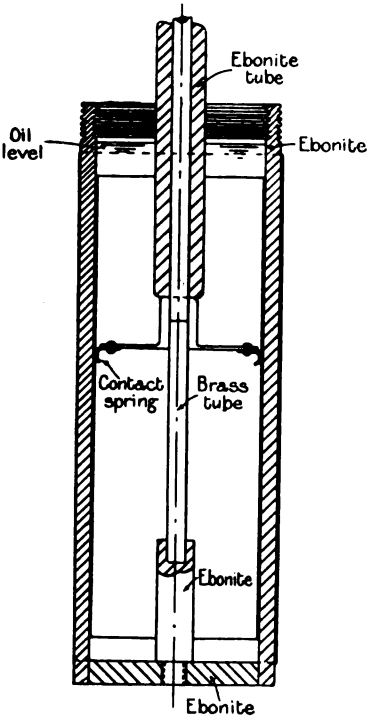

FIG. 4.

A datum reading being taken with the electrodes in contact, their distance apart could always be obtained provided the air-pressure in the case was the same. The case, it was found, stretched 0·001 in. for every 40 lbs. air pressure, so that one had to be careful to allow for this, as otherwise serious errors might be introduced.

The air to be tested was stored in two large steel tanks many times the capacity of the case. After allowing it time to settle it was drawn through a tube containing dry calcium chloride in order to remove any water vapour, and then through a plug of asbestos in order to remove

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any particles of dirt or $CaCl_2$ which might have been carried over with it. The tests are thus intended to represent the behaviour of dry air, and the results might be slightly modified if water vapour were present.

As already mentioned, measurements were made both with alternating and direct currents, the object of this being partly to see if it was possible to ascertain whether the maximum voltage of the alternating wave corresponded exactly to the direct-current voltage required, and partly because the method of measurement employed

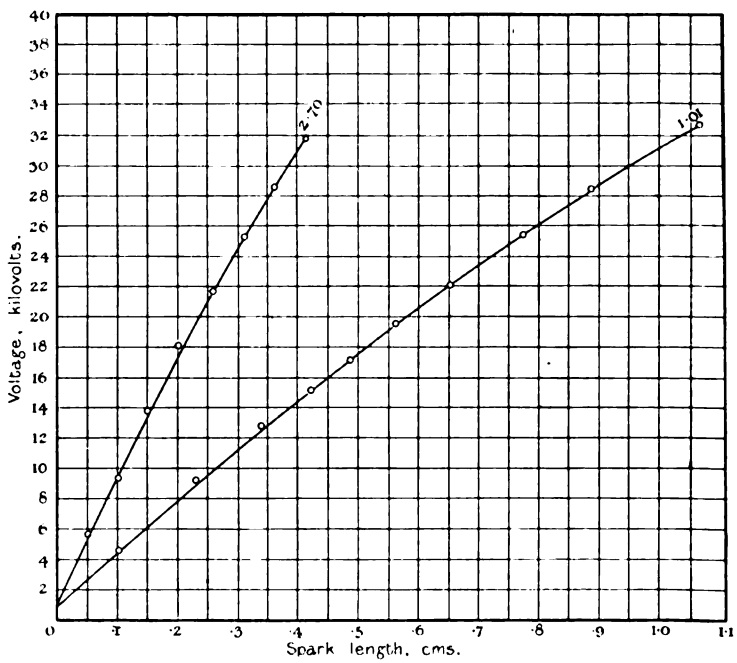

FIG. 5.—2·54 cm. Spheres, Alternating Current.

for the direct-current measurements was not applicable below about 20 kilovolts.

In the alternating-current measurements the maximum voltage was either obtained by multiplying the effective voltage by the amplitude factor obtained by a large Joubert disc, or later the maximum voltage was read directly by means of an electrostatic voltmeter connected across a condenser, charged by means of the Joubert disc at the correct point in each revolution of the alternator, the contact-maker being moved round until a maximum reading was obtained.

The voltage was read on the primary side of the transformer. This was, however, a fairly large one of the core type with a good

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magnetic circuit, and as it was on no load it had a negligible voltage drop. The secondary was divided up into ten sections, so that the voltage ratio was obtained accurately while working in the region of its normal flux by measuring the ratio of each section independently.

The ratio of the transformer was 104·5 to 1, the frequency of supply 50 cycles per second, and the maximum effective voltage 20,000, which with the wave shape used (a very peaked one) corresponded to a maximum voltage of about 32,500 volts.

Direct-current Measurements.—These were intended to range up-

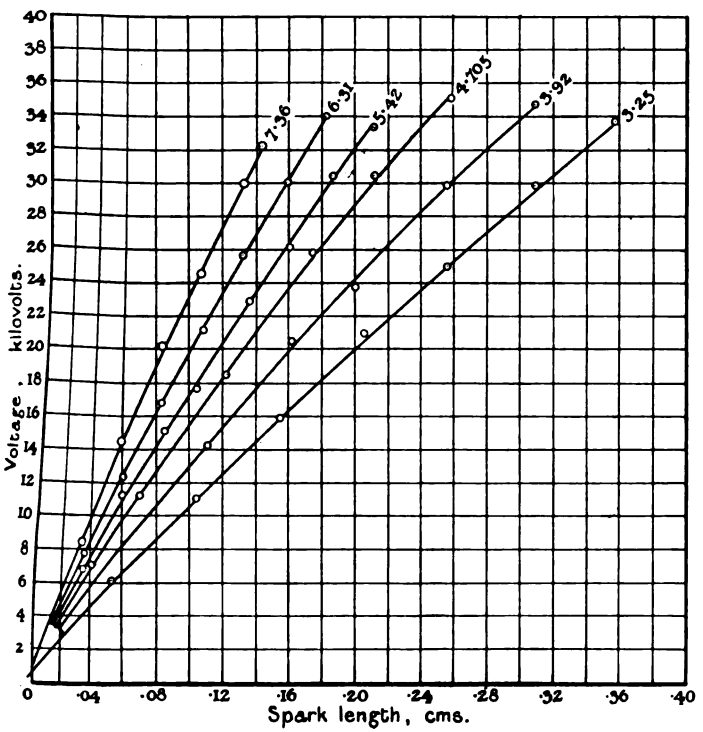

FIG. 6.—2·54 cm. Spheres, Alternating Current.

wards from about 20,000 volts, *i.e.*, rather less than the maximum limit of the alternating-current tests to as high a voltage as could be obtained.

For measuring the voltage, the method described by the author in a previous paper * was employed slightly modified and improved.

The method, it may be mentioned, consists in connecting two condensers in series across the spark-gap. These condensers have their outer coatings connected to some form of micro-ampere meter, which

* *Journal, Institution of Electrical Engineers*, vol. 37, part 180, p. 295.

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is shunted by a small spark-gap of a few thousandths of an inch, while choking coils are interposed between the condensers and the micro-amperemeter.

The charging current of the condensers being a steady flow, passes through the micro-amperemeter and deflects it; the discharge, being oscillatory, jumps the auxiliary gap and is not recorded. Hence we are enabled to measure the charging current. Knowing the capacity of the condensers and the frequency of the sparks, the voltage is readily calculated.

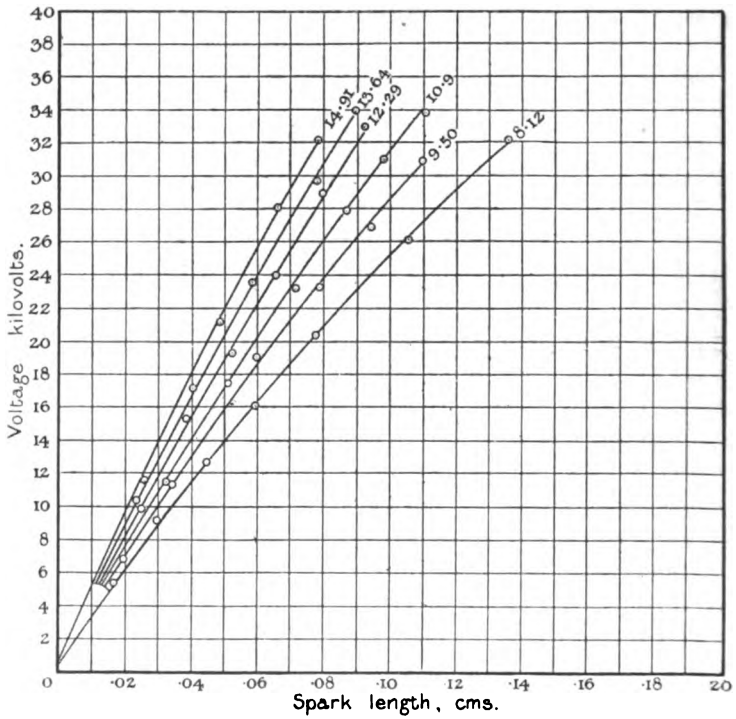

FIG. 7.—2·54 cm. Spheres, Alternating Current.

The only objection to this method was that as no influence machine gives a current quite independent of the voltage (although in some cases it is nearly so), unless the micro-amperemeter was very sluggish the reading obtained was not quite steady.

In order to overcome this difficulty the arrangement shown in Fig. 3 was adopted. In this arrangement two high resistances of about 0·5 megohm each were connected in series with the micro-amperemeter, one on either side, so as to secure symmetry. These, with the normal current of the machine, gave a pressure drop of about 8 to 10 volts.

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Across this combination was connected a condenser of about 15 microfarads capacity, and of a leakage resistance of some thousands of megohms. This arrangement acted as a store for a considerable quantity of electricity, so that a perfectly steady deflection readable to ½ of 1 per cent. could be obtained.

A great deal of trouble was experienced with the high-tension condensers. If a high order of accuracy is to be obtained it is essential that the spreading of the charge at the edge of the coatings observable in any ordinary condensers should not be allowed to take place, as it

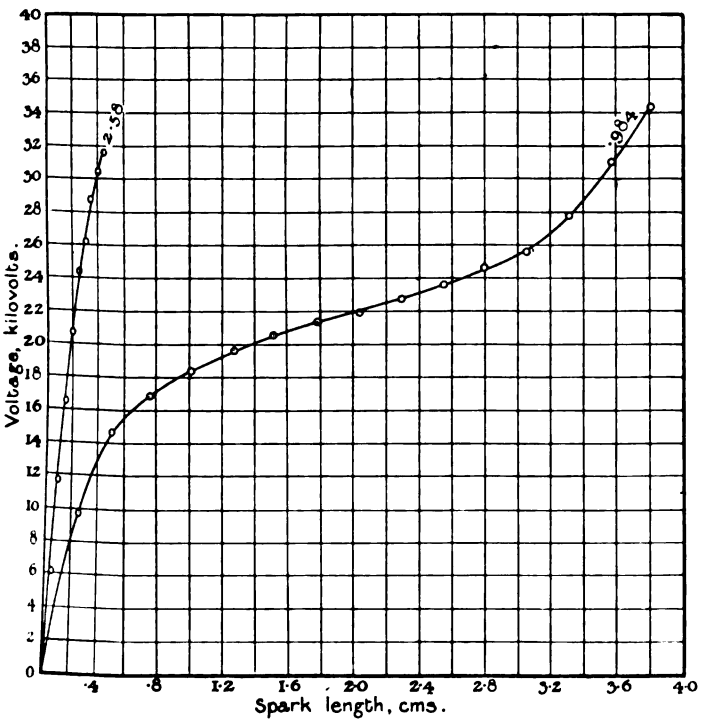

FIG. 8.—0·3175 cm. Spheres, Alternating Current.

means an increase of capacity at high voltages, introducing errors in the results. Also it is important that the leakage current passing through them should be negligible compared to the charging current.

The first condensers employed consisted of ebonite sheets coated on both sides with tinfoil and immersed in insulating oil. It was found, however, that these leaked very badly, the current passing through the oil itself. Various kinds of oil were tried, but even the best insulating oil seemed to pass sufficient current to cause large errors which could not be corrected for. The next condensers used

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were made of ebonite tube $\frac{1}{8}$ in. thick and $3\frac{1}{2}$ in. inside diameter, coated inside and out, but with the inside coating considerably shorter than the outside one. They were closed up at the bottom and filled with insulating oil. The oil stopped the spreading on the inside, and the greater length of the outside coating relieved the dielectric stress at the edges and prevented it on the outside.

These condensers, however, were short-lived, as after being in service a few minutes they broke down, the puncture occurring at the edge of the inside coating where the dielectric stress normally re-

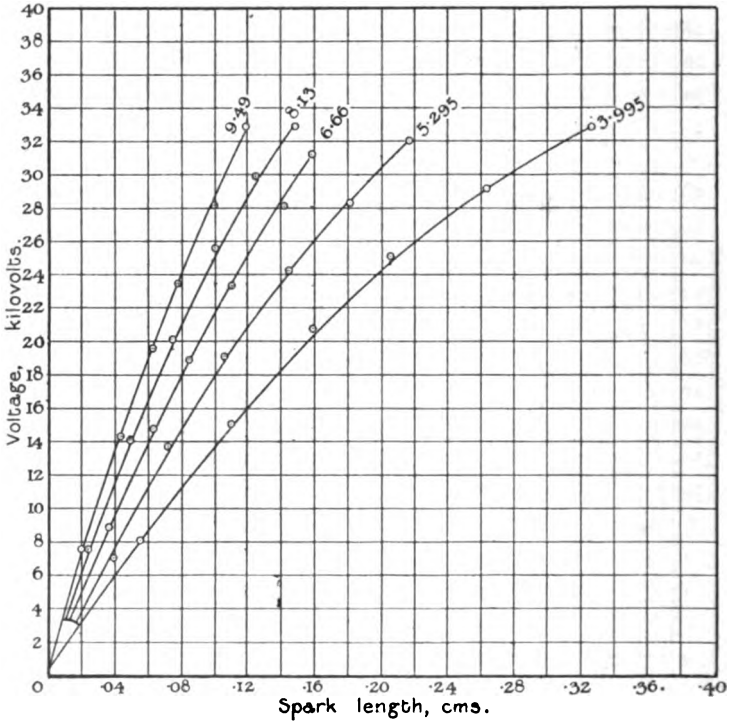

FIG. 9.—0·3175 cm. Spheres, Alternating Current.

lieved by the spreading had been concentrated by the use of oil. Next some Moscicki condensers were obtained. These, as is well known, consist of glass tubes with thickened ends, the thickening serving to reduce the potential gradient at the edges. These stood the voltage without puncturing; but, unfortunately, passed a leakage current which, although not of importance in engineering work, was yet sufficient to affect the proposed measurements. Glass, in fact, although excellent as regards its dielectric strength, is not as a rule from the point of view of insulation resistance anything like as good

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as ebonite, and it is probable that it was through the glass of the condensers that the leakage took place.

The next condensers used were similar to the second ones, *i.e.*, they consisted of ebonite tubes coated inside and out, and filled with oil, but the thickness was increased to 8 mm. These are shown in Fig. 4. For a long time they answered satisfactorily, but eventually punctured at 75,000 volts. The puncture was repaired, and they were used for all the direct-current measurements given. Their breakdown at 75,000 volts or 37,500 volts on each may seem surprising considering the

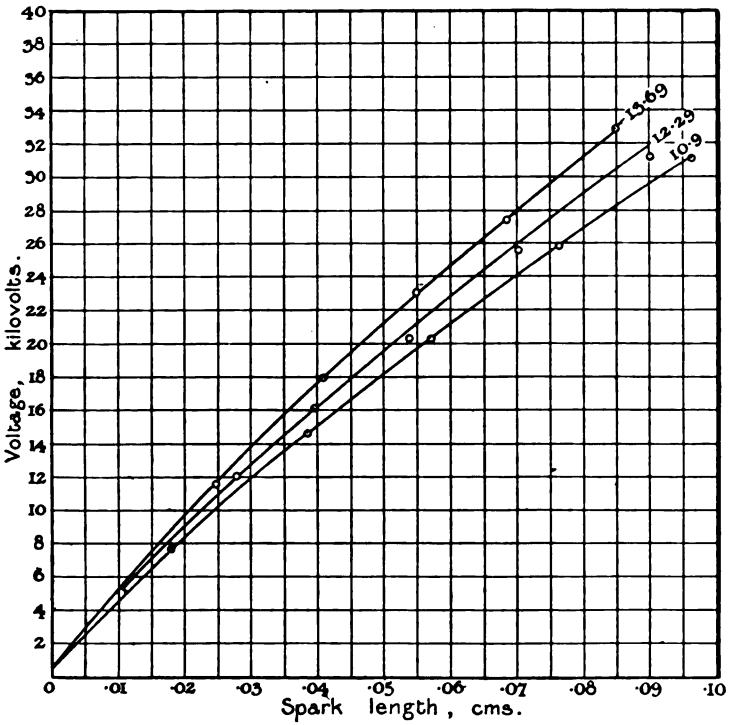

FIG. 10.—0·3175 cm. Spheres, Alternating Current.

great thickness of ebonite used, but shows what may happen when the dielectric stress is concentrated by a sharp edge as in this case. An endeavour was made to carry the voltage higher by using condensers employing compressed air as the dielectric. The plates of these condensers were of tin-plate, edged by a beading of brass wire so as to cover up all sharp edges, and placed in a cast-iron case containing dry air at a pressure of 200 lbs. per square inch. These were designed to carry 100,000 volts each, but although they did not break down they passed such a large leakage current as to be quite useless. This

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leakage current is probably due to almost microscopic particles of dust settling on the plates and acting as sharp points from which a brush discharge takes place. No amount of filtering and cleaning served to entirely get rid of this trouble, and their use had to be abandoned. It is not likely, however, that anything would have been gained by taking the voltage above that attained by the use of the ebonite condensers, as there is no reason for doubting that the same laws would hold. The measurements are therefore left at this point.

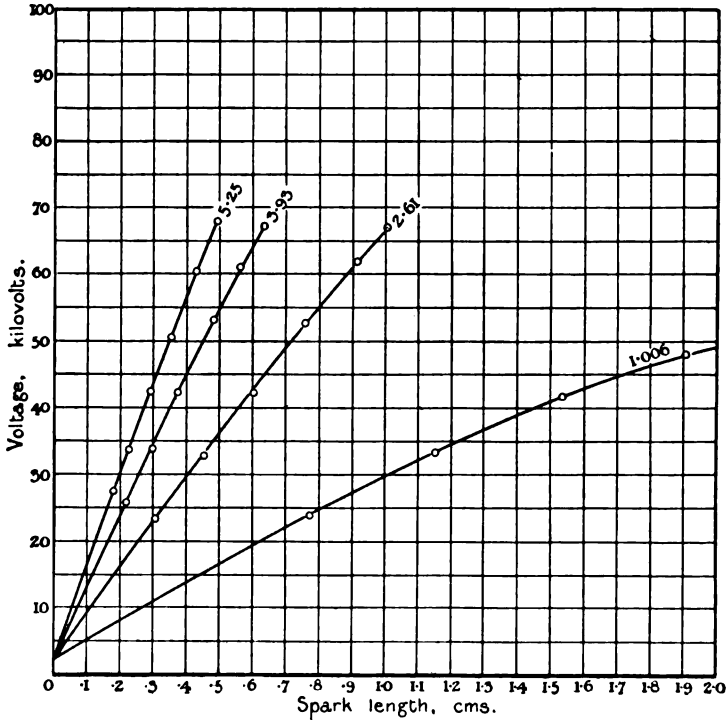

FIG. 11.—2·54 cm. Spheres, Direct Current.

Measurements Made.—Figs. 5, 6, and 7 show the curves obtained with spheres 1 in. diameter using alternate current. They are very nearly straight lines, as the distance apart was in all cases, except that at atmospheric pressure, small compared to the diameter of the spheres. Figs. 8, 9, and 10, which give the results obtained with $\frac{1}{8}$ in. (0·3175 cm.) spheres, are of more interest. In these the curves which are nearly straight lines at the high air pressures where the spark length was small, bend over more and more as the pressure is lowered and the spark length corresponding to a given voltage increased. These

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curves show that one must beware of making the statement which is sometimes done that the spark length is inversely proportional to the gas pressure. Such a statement only applies when the radius of curvature of the electrodes is indefinitely large.

To take an extreme case, we see from reference to the two curves in Fig. 8 that a voltage of 24 kilovolts will spark 2·53 cms. at atmospheric pressure, but only 0·26 cm. or little more $\frac{1}{10}$th of this amount under a pressure of 2·58 atmospheres or 23 lbs. per square inch. Hence under

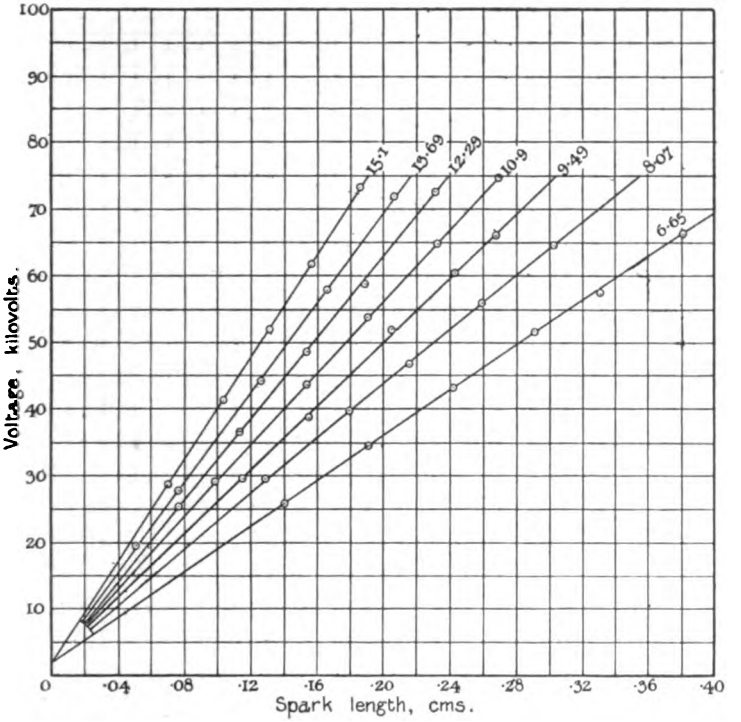

FIG. 12.—2·54 cm. Spheres, Direct Current.

certain conditions a small increase in the air pressure will effect a very great decrease in the liability to breakdown.

Figs. 11 and 12 show the curves obtained with the larger spheres using direct current. The fact that although taken with higher voltages these are much nearer to straight lines than the corresponding alternating ones, is probably due to the distance in the case of the alternating ones being small. The direct-current curves give a value for the dielectric strength not varying more than 1 per cent. from the mean for any batch of curves. Indeed, the maximum variation was generally nearer $\frac{1}{2}$ per cent., while the alternating curves did not do so,

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but gave a value which decreased as the gap length increased. It should be noted that the direct-current voltage distance curves appear to radiate from a point whose ordinate is about 3 kilovolts. The alternating tests appear to show that they do not really pass through this point but bend round and cut the axis at a value considerably lower than this. (Note: Minimum voltage required to produce a spark in air.)

Figs. 13 and 14 show the curves for the small spheres (0·3175 cm. diameter) obtained with direct current. These are similar to the alternating-current ones, but, of course, bend over more. It will be

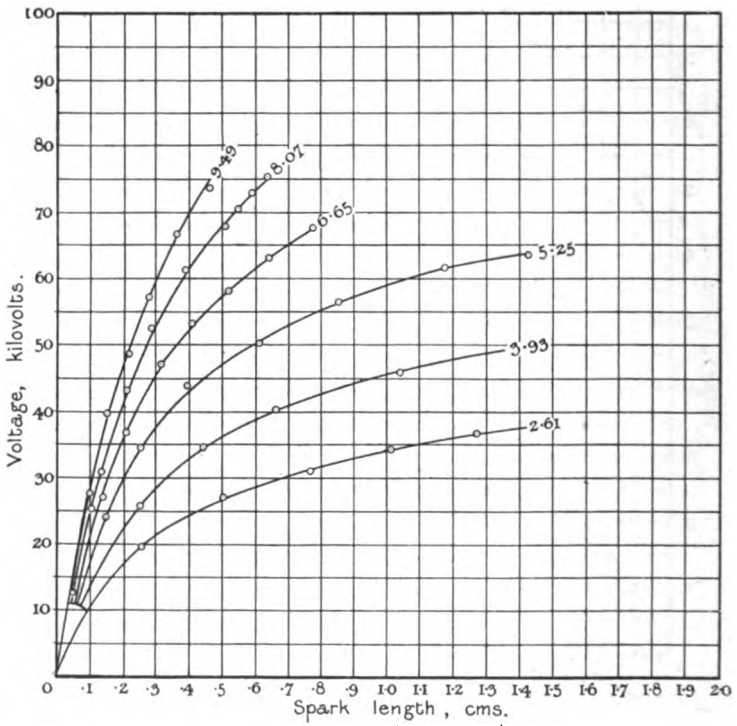

FIG. 13.—0·3175 cm. Spheres, Direct Current.

noticed that the three lowest pressures stop against a vertical instead of a horizontal limit. This was because the limiting factor was not the voltage which the condensers would stand, but the formation of a corona on the electrodes. An influence machine not being capable of supplying any quantity of power, as soon as the corona commenced to form the leakage current which flowed dropped the volts of the machine to such an extent that sparks could not be obtained. The fact that all these curves stop at the same gap length shows that the distance apart at which the corona forms is independent of the gas

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pressure and depends only on the shape of the electrodes. This shows that it is not possible to prevent the formation of a corona on a spark-gap previous to the actual discharge merely by placing it in compressed air. If a given gap gives a brush discharge before a spark in ordinary air it will also do so under pressure.

Fig. 15 shows a set of curves taken chiefly as a check with two spheres 0·635 cm. (¼ in.) diameter and direct current. The corresponding curve at atmospheric pressure will be found in Fig. 1. It will

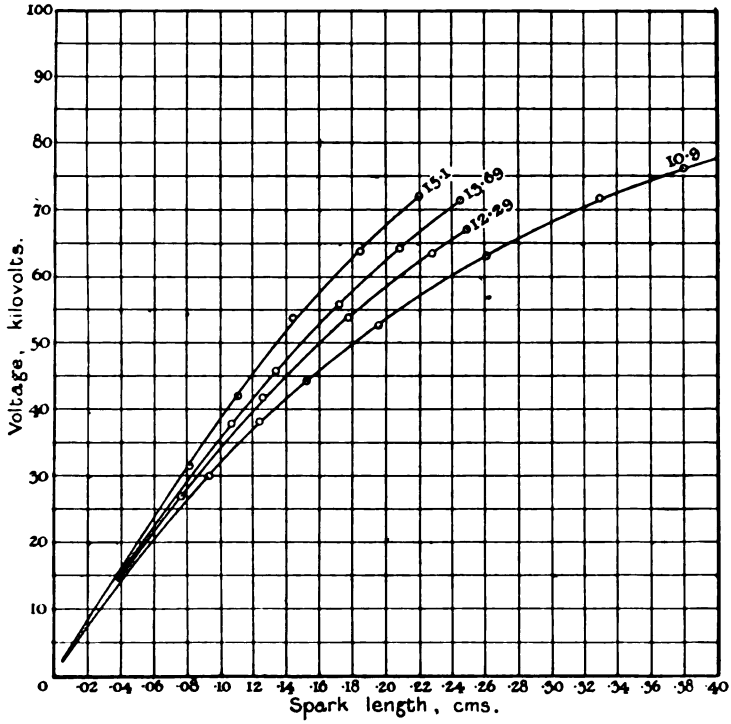

FIG. 14.—0·3175 cm. Spheres, Direct Current.

be seen that, as is to be expected, they occupy intermediate positions between those already given.

Values of the Dielectric Strength deduced from the Results.—In attempting to deduce some standard figures for the dielectric strength of air from the results given, only the direct-current measurements have been employed. The reasons for this are: Firstly, that in the alternating-current measurements the distances are extremely small; and secondly, that the direct-current measurements could be made with a greater degree of accuracy than could the alternating ones. This was supported by the fact that the regularity of the points

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obtained by the direct-current method was distinctly superior to that obtained by the alternating.

The results obtained are plotted in Fig. 16. It will be seen that those obtained from the different spheres do not agree with one another as should be the case, but are greater the smaller the spheres employed. For the largest spheres the mean value of the measurements at atmospheric pressure gave 38·85 k.v.-cm. as the dielectric strength of air. This agrees very well with the figures

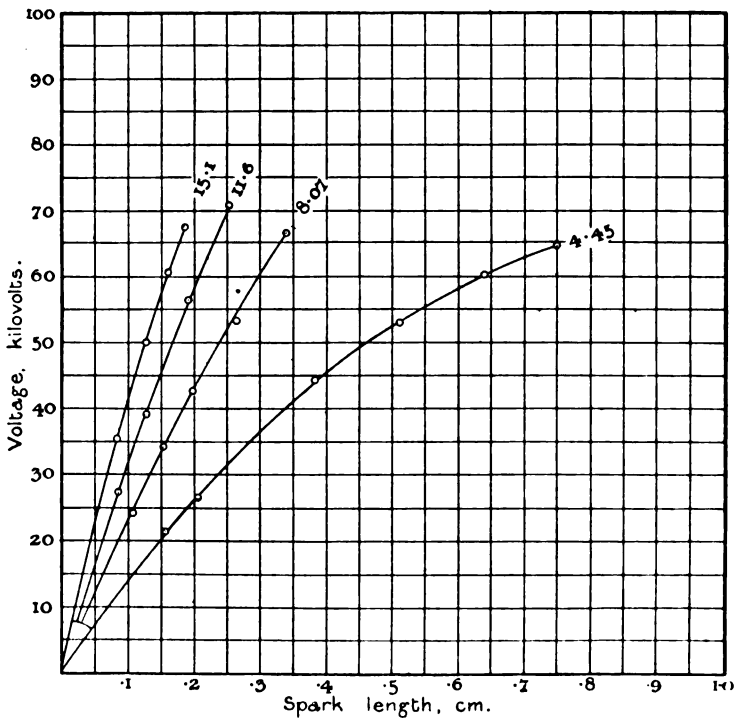

FIG. 15.—0·635 cm. Spheres, Direct Current.

given by Dr. Russell. It is, if anything, slightly higher than most of those given by him, the average being about 38 k.v. per centimetre, but the electrodes from which this figure was obtained appear to have been larger than those used by the author.

Taking the curves as a whole, we see that they are very nearly straight lines, not passing through the origin, but cutting the axis of zero pressure at a point which for the case of the larger spheres is about 12 k.v. per centimetre, and in the case of the small ones is even higher.

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It is not easy to say why the results from these different-sized spheres should not be in closer agreement. It can hardly be due to the formula deducing the dielectric strength being in error, for if this were so it is scarcely likely that the values of the dielectric strength obtained from the various points on one curve should be constant to anything like 1 per cent.

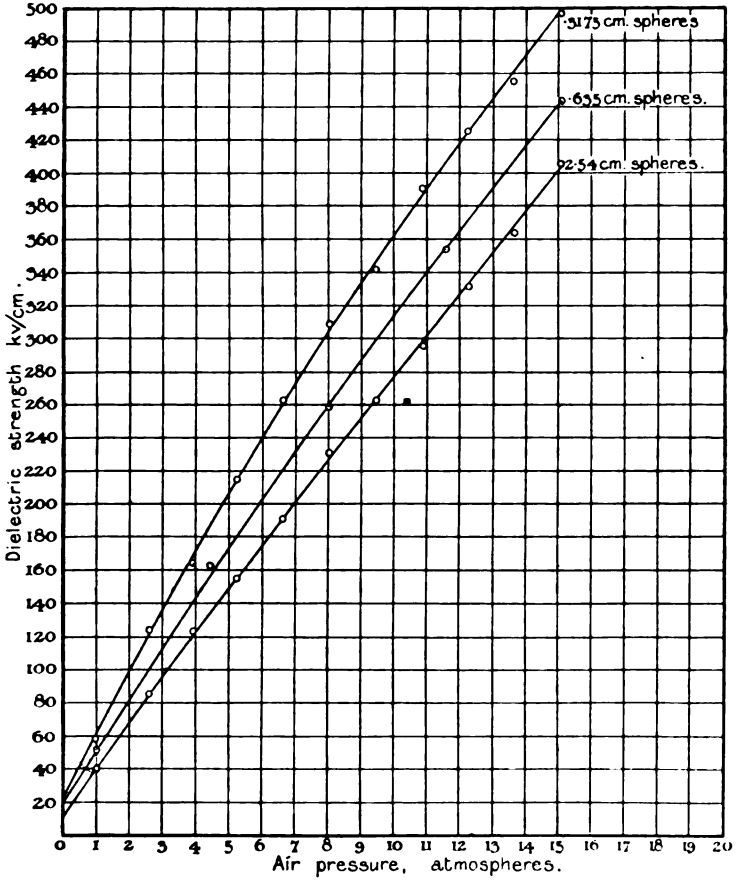

FIG. 16.—Relation between Dielectric Strength and Air Pressure.

Neither can it be due to distortion of the electrostatic field by the rods which carried the electrodes on their ends, for in all cases these were made the same fraction ($\frac{1}{4}$) of the diameter of the electrodes.

It might, of course, be due to the presence of the surrounding case, but as this was large compared with the size of electrodes,

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this explanation hardly seems possible. The supposition of a layer of air on the surface of the electrode of greater strength than the main body, which we saw would explain the delay in production of the corona, would also serve to explain this if we assumed that the thickness of the layer was independent of the diameter of the sphere.

For practical purposes, however, we may take the lower curve of Fig. 16 as being nearly correct, and also, if anything, being on the safe side. We see from it that the dielectric strength of air at ordinary temperature (17° C.) follows very nearly a linear law, but that the curve when produced back does not pass through the origin—that is to say, that the dielectric strength cannot strictly be said to be proportional to the pressure.

The actual values of the dielectric strength can be obtained from the curves given. If an empirical formula be desired, the equation—

$$\text{Dielectric strength} = 20 + 25{\cdot}6\ (\text{pressure})$$

expresses the relation with sufficient accuracy between the pressure of 3 and 15 atmospheres absolute.

It will be seen that under pressures readily obtained in engineering work the dielectric strength reaches high values, equal to that of a solid or liquid dielectric. Compressed air as an insulation has considerable possibilities for certain cases as it is free from viscosity and residual charge effects, and is not permanently injured if it is broken down.

The author would finally express his indebtedness to the University of Liverpool for facilities for carrying out the work, and to Professor E. W. Marchant for much advice and assistance, both during the progress of the work and in the preparation of the paper.

Discussion.

Dr. Russell.

Dr. A. Russell: Following the usual custom, Mr. Watson talks about the "dielectric strength." Principal Carey Foster uses the simpler phrase, "electric strength," and it seems to me there is much to be said in its favour. Dielectric strength does not tell us anything more than electric strength—electric strength is quite descriptive enough. I do not quite agree with the author's account on page 114 of what I proved. It is true that if the minimum distance between the spheres is less than the diameter of either a disruptive discharge will ensue. That is all I wanted to prove, because at that time I was measuring electric strengths by using spherical electrodes, and so I had to satisfy myself that their use led to correct results. The statement, however, that if x is greater than $2a$, $\frac{dR}{da}$ is negative, and therefore a corona will form, I do not agree with, because the assumption of a uniform layer of disrupted air cannot be used to prove that a disruptive discharge will not take place. When you have the two electrodes close together the

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Dr. Russell.

maximum electric stress occurs at the two points of the spheres which are closest together, so that really you will have little "blisters" of disrupted air at these two points, and the shapes of the equi-potential surfaces are no longer spherical. Hence in this case we cannot apply the simple theory. To work out the complete theory would be very laborious, but it would probably be found that the distance at which a corona formed could be calculated. Mr. Watson has shown how to find this distance experimentally. It occurs where there is a point of inflection on one of the curves shown in Fig. 1. I congratulate the author on the very ingenious voltmeter he uses. A voltmeter of this type, however, must be rather laborious in practice. In Fig. 16 the author gives the different values he obtained for the electric strength of air when using different sized spheres. The variations are not large, but it is unsatisfactory that all the points do not lie on the same straight line. I do not think his suggestion of a layer of air round the spheres of greater electric strength than the remaining air very convincing. I think a simpler explanation could be made up from considerations of what used to be called the "minimum sparking potential" between electrodes. Professor Strutt has shown that the potential difference between the cathode and the negative glow is constant and equal to about 350 volts whatever the pressure of the air. As the pressure of the air increases the negative glow approaches the cathode and ultimately apparently disappears into it. If we assume that the pressure on the Faraday tube, which is subjected to the maximum stress, is not the potential difference between the spheres, but is this potential difference *minus* 350, then I think this assumption would be sufficient to explain why the lines in the diagram are not coincident. The formula the author uses is that the electric strength R′ equals the potential gradient V/x multiplied by a certain factor f. I call R′ the apparent electric strength. The real electric strength R possibly may be got by the formula—

$$R = \frac{V - \epsilon}{x} f = R' - \frac{\epsilon}{x} f,$$

where ϵ is the potential difference between the cathode and the negative glow. Assuming this, we see that the apparent electric strength $= R + \epsilon (f/x)$. Now for a given value of x, f/x diminishes as the radii of the spheres increase. This explains, therefore, why R′ is smaller for the large spheres. If x be not greater than a we can use the very simple formula—

$$\frac{f}{x} = \frac{1}{x} + \frac{1}{3a}.$$

By giving a suitable value to ϵ I think we could manage to get these lines much closer together. Of course this theory is not quite satisfactory; it would only be satisfactory if ϵ came out equal to 350. I analysed many results some years ago, and came to the conclusion that ϵ was about 800 volts, so that the agreement with theory was not quite satisfactory. In using the formula for the electric strength it has to

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Dr Russell. be remembered that it cannot be used when the distance between the electrodes is less than about a millimetre, because the ionisation in this case is excessive, neither can it be used when a corona is formed. The other cases in which it cannot be used are with very high-frequency pressures, such as occur in wireless telegraphy and with impulsive rushes of electricity. For instance, we cannot apply this formula very satisfactorily to make calculations in connection with the spark-gaps used for safety devices in transmission lines. With an impulsive rush of electricity the sparking distance seems to be absolutely independent of the shape of the electrodes. Sir Oliver Lodge showed this experimentally to this Institution twenty years ago,* when he read his classical paper on lightning conductors. The frequency at which these formulæ cease to be applicable has yet to be found out. For values of the frequency up to about 100 I know that they are very approximately true.

Mr. Paterson. Mr. C. C. PATERSON: The author complains that the results of his alternating-current measurements were not so easy to obtain accurately as the direct-current measurements. I think, however, that if all his observations fell as well on the curves as those do in Fig. 6, for instance, there is not very much to complain of on that score. In connection with the possibility of repeating these results, I should like to ask him whether he found that the degree of polish which he had on his spheres made any difference to the result. We have been warned by American observers that it is very important to clean the electrode every time a discharge takes place. I shall be interested to hear if he has found any difficulty in that way. Then he conducted all his experiments in a closed cylinder, in which the air must have become very thoroughly ozonised. I do not know whether the dielectric strength of ozonised air is any different from that of air which is freer and less ozonised, but one would be interested to know if the author made comparative tests in the cylinder and outside the cylinder to see if this made any difference—of course, under ordinary air pressures. I am very interested in the remarks on page 125 about the difficulty found in getting the ebonite to hold up. We have recently been making a long series of measurements on the dielectric strengths of different kinds of ebonite, and the figure comes out at something like 50,000 to 100,000 volts per millimetre. The author's 8 millimetres of ebonite broke down at something like 30,000 or 40,000 volts. That does show, as he says, what enormous stresses we can get in insulating materials, if the ideal conditions of an equal potential gradient are not there. I think the conclusion to be drawn from that is, that even though we use very great ingenuity in devising the shapes of the electrodes and the conditions of test so as to get a really even potential gradient in the materials, and get the true value of the dielectric strength of the material, yet in calculating thicknesses for practical use it is just as well to use a multiplier of 10 or 20 as a factor of safety. As an illustration of this, when we were breaking down some sheets of very thin

* *Journal, Institution of Electrical Engineers*, vol. viii., p. 386 (1889).

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ebonite (about $\frac{1}{16}$ in. thick), we used ordinary flat circular electrodes with well-rounded edges and about $\frac{1}{4}$ in. thick. The ebonite broke down at about 40,000 volts, but the failure invariably took place about 1 in. away from the circular disc, showing that the stresses were uneven, and that the ordinary stresses obtained in practice are enormously greater than those which can be introduced from the spherical electrodes properly imbedded in the insulating materials. Mr. Paterson.

Dr. G. KAPP: I have no information to add to that given by the author, but from a practical point of view I am greatly interested in this question, as every engineer is who has to consider high voltage work. The experiments undertaken by Mr. Watson were not only with high pressure in an electric sense, but with high air pressure also. For atmospheric pressure the subject has been studied by others, notably Professor Ryan, who about five years ago published a formula giving the maximum voltage between parallel wires. It is not a question of sparking from wire to wire, or, so to speak, completely breaking down, but rather for what may be called the brush discharge, which, I understand, also enters at some stage of the gradual increase of potential difference between the spherical electrodes used by the author. It would be useful to have some information as to what the electric stress will be if the air pressure were reduced below atmospheric pressure. The author's apparatus, which I was fortunate enough to see at Liverpool, is perfectly adapted to work with pressures above and pressures below atmosphere; and it would be possible, without departing from the method of the experiments, to ascertain whether the curves continued backward into a region of less than atmospheric pressure retain their character, or what other than a linear relation between voltage and air pressure may exist. The practical application of this point is obvious. In power transmission lines the limiting voltage is that at which a brush discharge from wire to wire begins, and that limit seems to be influenced by the barometric pressure. Engineers who have to do with power transmission know perfectly well that brush discharges are more likely to occur in high altitudes than in the plain, and Professor Ryan * gives this formula for the crest value of the voltage between wires: — Dr. Kapp.

$$E_{max.} = \frac{17{\cdot}94b}{459 + t} \times 350{,}000 \log\left(\frac{s}{r}\right)(r + 0{\cdot}7).$$

b = barometric pressure in inches of mercury.
t = temperature in Fahrenheit.
s = distance between wires in inches.
r = radius of wire in inches.

It is a very complicated formula, but it is the only formula available at present. We should like to have, if possible, a simpler formula, but, above all, we should like a confirmation of it. Now the author's apparatus could be used to confirm or otherwise the proportionality

* *Proceedings of the American Institute of Electrical Engineers* (Meeting of February 26, 1904).

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Dr. Kapp. between $E_{max.}$ and b indicated by Ryan's formula. Perhaps the author could also use instead of spheres electrodes so shaped as to represent parallel wires, and then he would be in a position to verify the other terms in the formula. The tests should not be as to the breakdown or spark voltage, but as to the point where the brush discharge begins, because it is that point which in power transmission one has to consider as the limit at which one loses electricity and the line ceases to be efficient or safe.

Mr. Rayner. Mr. E. H. RAYNER: On page 113 the author quotes Dr. Russell, and mentions the factor f. In Dr. Russell's paper, as those who have studied the question know, he gives two values for f—one to be used when the earth potential is half-way between the extreme potentials, and the other to be used when one of the electrodes is at earth potential. The results for the dielectric strength of air will vary considerably between the two cases, especially if there is a long distance apart between your spheres. When the spheres are close together it does not matter what the earth potential is relatively to the other two. But the author does not state anywhere whether he has been careful to keep his balls equally distant from the earth potential, or whether one of them was at earth potential. It is, of course, perfectly easy for alternating-current work to ensure definite conditions. By earthing the middle of the transformer, or one end of the transformer, we can absolutely fix them. But in direct-current work, where we are dealing with two condensers, as the author does, it is not possible to locate the position in the system of the point of zero potential to earth, and I cannot quite see how actually to fix the earth potential relatively to the potentials of the spheres, except by connecting a high resistance across the high potential and earthing its middle point. It is evident from Dr. Russell's figure that we can get 20 or 30 per cent. error if we are not careful to fix the potential of the spheres relatively to the earth potential. As to the measuring of direct-current voltage, there are one or two quite important points on which I should like a little further information. The first is that the author is dealing here with the dielectric strength of a succession of sparks. Is that the proper dielectric strength? After sending one spark between two electrodes close together, as far as my experience goes the next sparks follow at a greatly reduced voltage, and that is the voltage that the author is measuring. That is my experience of alternating current. Here the first spark goes at a much higher voltage perhaps, and the rest below. He does not say anything at all as to the frequency of the sparks. When the air is ozonised, or whatever it may be, in the spark-gap, and that air is not quickly blown away, it seems to me to be possible to get a much lower sparking voltage after the first spark has passed; but I believe that by keeping up an air blast in the air-gap the discharge can be prevented from taking place. The author has taken very great trouble, and, I have no doubt, has spent a very great deal of time, on these high potential condensers for 40,000 volts. Having had some experience of testing ebonite, it is surprising

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Mr. Rayner.

that these edges give such trouble. I thought in reading the paper the author might have used some electrostatic, perhaps home-made, voltmeter, either of the Jona or Kintner type, which were on the market when this work was done. That would have saved a lot of trouble, because I believe they read satisfactorily up to 100,000 volts. The great trouble with direct-current work is that you cannot use a voltmeter that takes any appreciable current. At the National Physical Laboratory we have installed a voltmeter for 100,000 volts, but we have also made it take $\frac{1}{50}$th of an ampere, which is out of the question for a machine of this kind. The current might be reduced to $\frac{1}{10}$th of this, perhaps, but it would be probably more than the Wimshurst machine would give. The author has mentioned the leakage current with glass condensers, but he does not say how that was detected; possibly with an ammeter. If he has done anything in that line it would be interesting to know what the power factor of a high-voltage condenser is, because it is a most important point in connection with this method of measuring voltages.

Professor Morris.

Professor J. T. MORRIS: The author appears to have experienced difficulties in the use of the two series-connected condensers for the measurement of the high voltages produced by the influence machine. These difficulties are of two kinds: (*a*) The breakdown of the dielectric

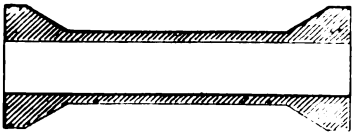

FIG. A.

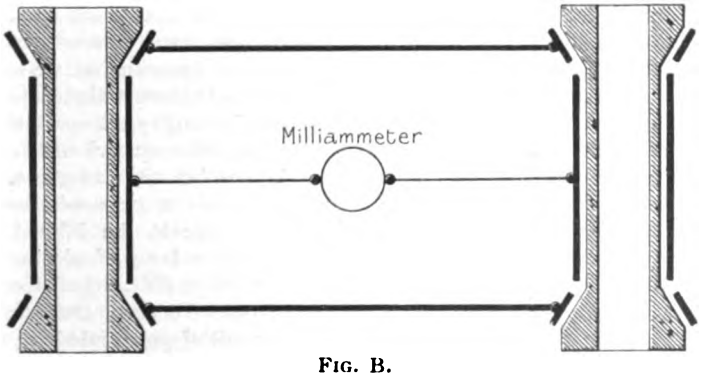

FIG. B.

of the condenser, and (*b*) the spreading of the charge at the edges. I think that these might be diminished in the following ways: First, to deal with the breakdown of the dielectric. Take an 8 mm. walled ebonite tube and turn it down to 2 mm. thickness, except for the ends, which turn as parts of two cones as in Fig. A. Then coat with

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Professor Morris.

tinfoil outside and in. In this way a much greater capacity would be obtained than by the author's arrangement, and with no greater risk of breakdown. In order to deal with the uncertainty of capacity resulting from a spreading of the charge at the edges, I suggest the introduction of two guard rings, one at each end of the tubular condenser, on the two sloping portions of the ebonite tube, and connected as shown in Fig. B.

Dr. Silvanus Thompson.

Dr. SILVANUS P. THOMPSON: I have very little to say, except to join in congratulating the author on having contributed a piece of work which will remain, at any rate for some years, as a substantial contribution to our knowledge of the subject of dielectric materials—that is to say, principally the air. I have been trying to compare the results given in the paper with those that we already possess from other sources, namely, the experiments conducted more than twenty years ago by Mr. Peace, and the experiments alluded to by Dr. Russell. One finds the extraordinary fact once more corroborated that the layers of air close up to a dielectric, when there is no brush discharge, are apparently stronger than those that are away from the surface of the conductors; in fact, thin layers are, taken in the gross, stronger than thick ones. Why should that be? We have a kindred fact, though the analogy must not be pressed too closely, in the behaviour of the arc. The apparent resistance of an electric arc is, for long distances, pretty nearly proportional to the length of the arc for a given strength of current; but for short distances between the electrodes you discover that the voltage required to send that current is not any longer proportional to the length. The arc acts as though it had something which discounts some 30, 35, 39, or 40 volts from the E.M.F. employed across it, and which is commonly (but erroneously) called the back E.M.F. of the arc, which may be expressed again in quite a different way, as though a thin layer of the arc close up to the crater offered a very considerable resistance. Here, in Mr. Watson's experiments, we have a phenomenon apparently of a layer of air close to the metal electrodes offering a greater resistance to breakage by piercing by the spark than the rest of the air. How are we to account for this very curious effect? I do not know—I do not think anybody knows, but one can guess. I think the explanation may be found—it is only a guess—in some difference in the dielectric capacity of the air in the immediate neighbourhood of the electrode; because if the layer of air in the immediate neighbourhood of the electrode has a different dielectric capacity from the air far away, the fall of potential per unit of length along that part will not be the same as the fall of potential along the rest. If we consider the distance between the two electrodes there is a certain fall of potential from one to the other. The curve representing the fall will not be a straight line. You have to take into account the equipotential surfaces to begin with. So far as they are pretty large spheres it may be nearly a straight line, except at the ends, where it will be flatter if the dielectric capacity is greater than that of the rest of the air, or more sloping if it is less. What is the fact?

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Dr. Silvanus Thompson.

Does the air in the immediate neighbourhood of the middle electrode act as though, when it is under the stress, it had a greater dielectric capacity than the rest of the air? If it has, we may reasonably think there is the beginning of an explanation.

I am a little puzzled at what appears at first sight to be a discrepancy between the facts indicated in some of these curves, and the facts indicated in others, and I would like the author to explain wherein the discrepancy lies. Let me particularise. If you look at the last figure in the paper, Fig. 16—which, I believe, is a summary of the results—we have there the electric strength in kilovolts per centimetre plotted against the air-pressure in atmospheres. Now let us examine some of the facts. For example, if we take 4 atmospheres pressure and run our eye up on that 4 atmospheres pressure line until we get to the highest of the three curves—which is the line corresponding to the small spheres, $\frac{1}{8}$ in. diameter—then apparently, for those small spheres, in a pressure of 4 atmospheres the electric strength is somewhere about 170,000 volts per centimetre. Turning back to Fig. 13, which relates to the same spheres, if we look for a spark length of 1 cm. and run our eye up, we shall observe that when we get to the curve of 3·93 atmospheres—practically 4 atmospheres—the electric strength is 45,000. Why is it 45,000 apparently in Fig. 13 and 170,000 apparently in Fig. 16? Again, take on Fig. 16 the atmospheric pressure, the ordinary air-pressure of 1 atmosphere, and run your eye up to the last curve, that for the 1-in. balls. Apparently in the 1-in. balls the atmospheric pressure of 1 atmosphere gives you an electric strength of 40,000 volts per centimetre. If you turn to Fig. 11, which deals with the 1-in. balls, and look at the spark-length for 1 cm., we have there 30,000 volts per centimetre, and not 40,000 volts. There is not so large a difference as in the other case, but still there is a difference. I am perplexed by finding these discrepancies—and there are several more—between the apparent facts; and I should be very much obliged if the author will explain why there are those differences.

May I draw the attention of the Institution to another of the branches of the industry in which this investigation will be of importance—I refer to the subject of wireless telegraphy. It is now something like ten years since Mr. Jervis-Smith, of Oxford, found that there was an important effect on increasing the pressure round the spark-gap in a transmitter; and quite recently he has been working at the same subject with really important results. We do not yet know all the advantages that are to be found in working with different pressures about a spark-gap. Probably the author's paper will contribute something that will have a bearing in that direction also.

Mr. Campbell.

Mr. A. CAMPBELL (*communicated*): The author's results are of interest in connection with the making of condensers for wireless telegraphy and for the subdivision and measurement of high voltages. Could the author give us any information as to how the permittivity (specific inductive capacity) of air varies with the pressure? I think

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Mr. Campbell.

this has been investigated. With regard to the excessive leakage noticed in the high-pressure air condenser, I may mention that even at quite moderate voltages dust filaments sometimes cause troublesome leakage in standard air condensers. If, however, they are designed with a minimum distance between the plates of 3 to 4 mm., the trouble disappears. In the case of those for very high voltages possibly the leakage would be diminished by covering the plates with a layer of ebonite "cured" on, or even of paraffin wax.

Professor Marchant.

Professor E. W. MARCHANT (*communicated*): The results obtained by Mr. Watson in this paper are of great interest. The dielectric strength of over 40 k.v. per millimetre found with air at 15 atmospheres should make the use of compressed air as an insulating material a matter for consideration in any transmission system designed for extra high voltages. The curves given in Fig. 8 are most remarkable, and the result that the sparking distance between small spheres is decreased to less than $\frac{1}{10}$ in. when the air-pressure is changed from 1 atmosphere to about 3 atmospheres shows how necessary it is to refrain from jumping at conclusions in work of this kind. The comparatively small dielectric strength of ebonite when working under continuous stress also is interesting; the usual value of the dielectric strength of 50 k.v. per millimetre is reduced to an apparent strength of 4·4 k.v. per millimetre. This is no doubt largely due to the sharp edge at which the breakdown occurred, but the effect of continuous dielectric stress is a subject which might well receive further attention. It should be noted that one of the great advantages of a dielectric like compressed air, which automatically seals itself, is that no effect of this character due to fatigue after long-continued stress can occur. The difficulties of obtaining accurate results with the small distances used by Mr. Watson in his experiments are very great, and the close agreement between his results with direct and alternating currents shows clearly how carefully his measurements have been made. The paper will, I think, be valuable in supplying accurate and reliable figures for the dielectric strength of compressed air, for which the results hitherto given have been very widely divergent.

Mr. Lustgarten.

Mr. J. LUSTGARTEN (*communicated*): I would like to draw attention to some of the deductions the author has made which do not quite agree with the experimental results of investigations on sparking distances in air at atmospheric pressure carried out by Messrs. Kemp, Stephens, and myself at the School of Technology, Manchester. We have used spheres, from $\frac{3}{8}$ to 3 in. in diameter, as electrodes, and found that inflections or "kinks" in the voltage-distance curves occurred with all spheres up to $1\frac{1}{2}$ in. diameter. We were unable to obtain kinks for spheres of larger diameter than $1\frac{1}{2}$ in., as they would occur beyond the voltage range of the transformer used, viz., 120,000 R.M.S. volts. In Fig. 1 the kinks appear at increasing sparking distances as the size of the sphere increases. It was noted that for any pair of equal spheres the position and form of the kink depended on the disposition of the spark-gap or of the wires leading to it, and upon the

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Mr. Lustgarten.

wave-form or frequency of the generator employed. Plate shields to the electrodes or an auxiliary gap also considerably affected the shape and position of the kink. When the electrodes were placed on tall glass pillars near the transformer, the kink differed from that obtained when the electrodes were well away from the transformer. In Fig. C are shown the kinks obtained with ½-in. spheres on two generators, the broken-line curve was obtained with a wave-form practically sinusoidal, and the full-line curve with a peaky wave-form possessing a prominent thirteenth harmonic. The voltages in these and in all cases are the maximum values deduced from the wave-form of the generators. The kink for the first generator is scarcely present, and the dotted line has been drawn to show what is probably the voltage-distance curve independent of the character of the circuit. The indefiniteness of the kink (and even some part of the voltage-distance curve beyond it) points to a disturbance due to a condition of the electric circuit, and a very probable explanation of this is *resonance*.

No kink should appear if resonance is absent, and we should obtain a curve similar to that shown, with a dotted line for ½-in. spheres, in Fig. C, or to the needle-point curve. The initial and most definite portion of the curve has a regular curvature and then becomes almost straight. A small kink may occur with needles if the wave-form of the generator be suitable, but at very small sparking distance. In support of the resonance hypothesis I may mention that kinks occur in sparking-distance curves for oils, alternating current being employed. With direct current we should expect no kink in the voltage-distance curve, and on plotting Algermissen's* and Heydweiller's† results ‡ such is actually the case.

When resonance occurs the curve commences to inflect *downwards* from the true shape and about the same time a point glow appears, sometimes simultaneously on both the spheres, or more usually on one of them first. This glow appears along the common axis, *i.e.*, at the shortest distance between the spheres. We are therefore unable to agree with Mr. Watson's view that the glow first appears when the curve takes the marked *upward* rise.

I am further unable to agree with this conclusion that the point of inflection for the spheres necessarily cuts the needle-point curve. It will be seen in Fig. C that the kink for 1½-in. spheres cannot possibly cut the needle-point curve and even the broken-line curve for ½-in. spheres (where resonance is not prominent) does not intersect it. But eventually for large distances the curves for spheres and for flat plates also tend to meet the needle-point curve, and it has been shown by experiment that for very large distances the voltage-distance curve is independent of the shape of electrodes.

Referring to the distance at which the glow or corona first appears, in the case of small spheres it is about $4a$–$6a$, and $3a$–$4a$ for the large

* Zenneck, *Elektromagnetische Schwingungen und Drahtlose Telegraphie*, 1905 p. 1011.

† *Annalen der Physik und Chemie*, vol. xlviii., p. 785 (1893).

‡ Dr. Russell, *Phil. Mag.*, vol. xi. (1906).

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Mr. Lustgarten.

spheres, which is not in accordance with the hypothesis that it should occur at $2a$. This discrepancy cannot be attributed to the dielectrically stronger "layer of air" which the author mentions, since Dr. Russell's formula for $R_{max.}$ would not then give consistent results for a given pair

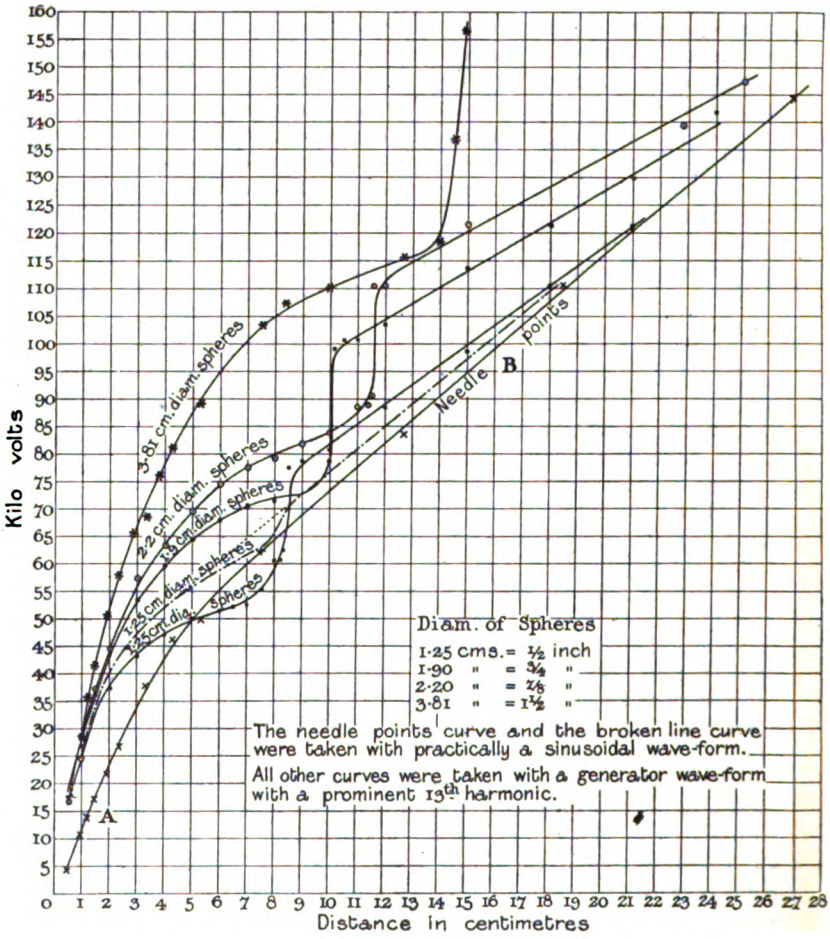
Kilo volts
Distance in centimetres
3·81 cm. diam. spheres
2·2 cm. diam. spheres
1·9 cm. diam. spheres
1·25 cm. diam. spheres
1·25 cm. dia. spheres
Needle points
B
A
Diam. of Spheres
1·25 cms. = ½ inch
1·90 " = ¾ "
2·20 " = ⅞ "
3·81 " = 1½ "
The needle points curve and the broken line curve were taken with practically a sinusoidal wave-form.
All other curves were taken with a generator wave-form with a prominent 13th harmonic.

FIG. C.

of spheres for distances from 2 mm. to $2a$, because for short distances the layer of air would be an important factor in the formula $R = \frac{v}{x} \cdot f$, and at larger distances in the neighbourhood of $2a$, would scarcely affect the value of x.

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This brings me to another point; the author quotes 38·85 k.v.-cm. as the dielectric strength of air at atmospheric pressure. Messrs. Kemp and Stephens have worked out the value of $R_{max.}$ for all spheres used in our experiments, and found that, using Dr. Russell's formula, the value for $\frac{1}{8}$-in. spheres is as high as **52**, and for 3-in. spheres as low as **33**. For 2-in. spheres the value was **37·0**, which is near to that quoted by Dr. Russell for this size. Using Baille's * results for flat plates R is found to have a value of **30**. Hence the dielectric strength of air is lower than **38** and probably lies between **30** and **33**. Our own

Mr. Lustgarten.

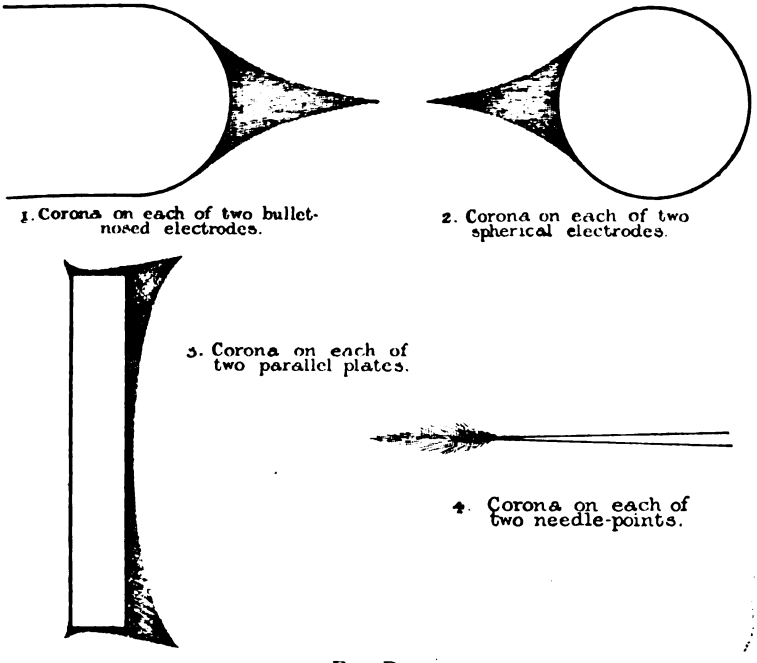
1. Corona on each of two bullet-nosed electrodes.
2. Corona on each of two spherical electrodes.
3. Corona on each of two parallel plates.
4. Corona on each of two needle-points.

FIG. D.

results and those of Steinmetz for parallel cylinders seem to bear this out. Hence the empirical formula for the dielectric strength of air under pressure is not correct, as the slope of the curve in Fig. 16 would be quite different for large spheres and therefore also for parallel plates.

It would have been interesting if Mr. Watson had given us a needle-point curve at increased atmospheric pressure, and had he worked with larger spheres it would have been interesting to know whether for a pressure of, say, 15 atmospheres the curves for larger spheres intersect those of the smaller spheres for short sparking

* "Conduction of Electricity through Gases," Sir J. J. Thomson, p. 387.

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Mr. Lustgarten.

distances, as we have found that this phenomenon occurs at atmospheric pressure. I note that on page 128, the voltage from which the direct-current curves in Figs. 11 and 12 radiate—viz., 3 kilovolts—is referred to as the minimum voltage required to produce a spark in air; the Hon. R. J. Strutt * has shown that 350 volts is the minimum.

I have mentioned above that curves for spheres bend over and eventually meet the needle-point curve. In explanation of this I suggest that the glow or corona from the commencement of its formation is "papilla-" or nipple-shaped, and that as the sparking distances increase the papilla becomes more nearly a true point discharge. If the brush discharge from the surface of a sphere be closely observed it will be seen that the extremity of the central ray is what we might truly take as a point, and thus the curves for spheres at large distances will ultimately merge into that for needle points. Till the papilla stage is established, the shape of the curves for a pair of spheres is practically represented by Dr. Russell's formula $R = \frac{v}{x} \cdot f$. Referring to the needle-point curve, if the distance between the extremities of the brush discharge be plotted instead of the distance apart of the needle points, the shape of the curve will, of course, be altered. If we assume that the voltage between the extremities of the brush discharges is the same as that which exists between the needle points, and that the length δ of the central ray of the brush is always a definite proportion of the distance between the needles, or what is virtually the same, proportional to the voltage, we shall get the part B of the curve rotated round so that its tangent of slope becomes greater. The initial slope of the part A of the curve will be greater than this modified part B because at short distances the needle points act as bullet-nosed electrodes rather than true points—such as the extremities of the central rays of the brush. The curve for needle points plotted to distances $x - 2\delta$ would then be practically linear for all distances. Fig. D shows the hypothetical coronæ on various electrodes. Applying the above hypothesis to the case of various-shaped electrodes, the shape of the voltage-distance curves can be satisfactorily explained.

Mr. Watson.

Mr. E. A. WATSON (*in reply*): Dr. Russell's remarks are extremely interesting and valuable, especially as he has paid a great deal of attention to the subject of the spark discharge between spherical electrodes. His explanation of the delay in production of a corona certainly seems quite feasible, but I am afraid that I cannot relinquish the assumption of a layer of air of greater electric strength than the main body in favour of an assumption involving a potential drop at the boundary of the electrodes. In the first place, I doubt whether under static conditions any such pressure drop exists, although it is certainly present when a discharge is taking place. Even, however, if it were present it would have to be of much greater magnitude than 350 or even 800 volts in order to satisfactorily account for the discrepancies noted with the smallest spheres.

* *Phil. Trans.*, vol. 193A, p. 377.

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Let us assume for the moment that such a pressure drop does exist, then considering a gap in which x is varied while the size of the spheres is kept constant we have, as Mr. Russell has pointed out— Mr. Watson.

$$\text{True electric strength} = \text{apparent electric strength} - \frac{\epsilon}{x} f,$$

which means that the apparent electric strength deduced from tests on the gap will not be a constant quantity but will vary with the distance apart of the spheres, being greater the less the value of x. This, however, is not the case, the value of the apparent electric strength derived from a given pair of spheres remaining constant over a large range of distances.

I believe that Dr. Russell himself in his earlier work allowed for a potential drop of 800 volts at the surface of the electrodes, but has since relinquished it as he found that more consistent results were obtained if it were neglected; at all events in his recent Institution paper no allowance is made for it.

Mr. Paterson raises a great number of interesting points. In the first place, in connection with the degree of polish of the spheres I am aware that American observers recommend that they should be cleaned and polished after every spark. I did not find that quite so much precaution was necessary, at all events with the direct-current tests. Of course it probably depends to a very large extent upon the amount of energy behind the discharge. In the case of the direct-current tests this was very small, never more than $\frac{1}{4}$ watt, and in the case of the alternating-current ones a very quick-acting circuit breaker was employed, set very closely. It also probably depends very much on the distance apart of the spheres. Of course any appreciable roughness of the surface cannot be permitted, but a slight amount of tarnish or discolouration seemed to have no appreciable effect.

Secondly, in regard to the conducting of the tests in a closed cylinder in which the air might become ozonised, I would point out care was taken in the design of the apparatus not to give any chance for brush discharges (which produce ozone) to occur. In fact, I am certain that ozone was not present, as the air, if allowed to escape, was quite free from smell. It must be remembered that a pure electric stress does not make ozone, neither does a disruptive discharge; it is only produced by brushes or coronæ.

I quite agree with Mr. Paterson as to the necessity for allowing a very liberal factor of safety in all insulation work, especially where there is no chance of the stress easing itself off. By this I mean that although a condenser made of a sheet of, say, ebonite coated with tin-foil and worked in air in the ordinary way may be worked with a fairly low factor of safety, yet if the same condenser be embedded or immersed in oil the factor of safety must be greatly increased. In the former case the low electric strength of the air permits the stress at the edges to ease itself off, whereas in the latter case this is not possible and breakdown occurs. The manner in which a breakdown spreads through a substance like ebonite and glass would, I think, form a

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Mr. Watson.

profitable source of study to any one desirous of a line of research. Professor Kapp's remarks as to the influence of barometric pressure on the brush discharge off wires are very important in view of the development of high-tension work, and I am at present putting in hand some experiments on this point. The only tests at present existing have the unfortunate drawback that those of one experimenter give results nearly twice as high as those of the other, although apparently the conditions of the two tests were the same.

Ryan's formula as quoted by Professor Kapp, although at first sight complicated, is really based on theoretical grounds. The theoretical formula should run—

$$E_{ax.} = 2\,\frac{b}{b_o}\,\frac{T_o}{T}\,R\,r\,\log_e\frac{s}{r},$$

where—

b_o is the standard barometric pressure.
T_o is the standard temperature (absolute).
T is the absolute temperature under the conditions prevailing.

R is the electric strength of air under standard conditions of temperature and pressure, and the other symbols have the meanings given by Professor Kapp.

The only alteration Ryan has made is the addition of 0·7 to the "r" term, this being made because he found that discharge occurred not from the surface of the wire but from a short distance away.

As regards Mr. Rayner's question whether the potentials of the two electrodes in the direct-current tests were symmetrical with respect to the earth, I feel fairly satisfied on that point. Both the middle point of the condenser system and of the influence machine were connected to earth. The condensers, moreover, were of the same capacity and passed no measurable leakage currents which might have disturbed the potential distribution.

The question as to whether the results, being the average of a train of sparks, do truly represent the electric strength of the air is an important matter. I believe, however, that they do so for the following reasons :—

1. The frequency of the sparks was low (about 2 seconds per spark).
2. The energy dissipated was very small, never more than 0·5 watt.
3. Records taken of the sparks on a Morse tape showed no signs of any increase in frequency (corresponding to reduced breakdown voltage) with time.
4. The high-tension voltmeter exhibited at the meeting was calibrated by means of a standard gap noting the deflection at the moment of breakdown. In no case was it observed that the first spark gave a higher reading than any of the succeeding ones.

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Mr. Watson.

I quite admit that in the case of alternating-current tests, especially if there is any power behind the discharge, the voltage required for the discharges following the first one might be greatly reduced, but I do not think that in my case anything of the sort occurred.

It would doubtless have been possible to have used some form of voltmeter for the direct-current tests, although a Jona one would not have been suitable, but it was thought that there would not be any gain by doing so; besides, it would have been necessary to calibrate it, which would have been a difficult problem.

The method employed may sound complicated, but it is not really so; in fact, fewer readings are necessary with it than if a voltmeter were used, owing to the way in which it automatically averages the results. If a voltmeter had been employed, each point would have needed about four or five readings, the average of these being taken. With the method described, however, only two are necessary, namely, the current and time of a given number of sparks.

The leakage current of the glass condensers was detected by opening the gap beyond the sparking distance. With good condensers the reading of the micro-ammeter would then fall to zero, with leaky ones it would not do so. I would point out, however, that this leakage current was only small, compared to the charging current, at any ordinary frequency, and for work at 50 cycles or so would have no noticeable effect upon the power factor. At the very outside the power factor due to the leakage current would not exceed 1 per cent. at this frequency.

I am much obliged to Professor Morris for his suggestions as to shaped tubes and guard rings. The question of shaping the tubes suggested itself when the earlier condensers broke down, but it was not done as the capacity was sufficient without, but if any more were to be made I think that I should embody some such arrangement.

Professor Thompson's suggestion that possibly the layer of air next a conducting surface has a higher permittivity than the main body would also serve to explain the facts noticed in connection with the small spheres. I do not know whether any one has studied the question of thickness and capacity of electrolytic films with sufficient care to be able to clear up this point quite definitely, but I believe that the permittivity of such a film is not far from unity, while its electric strength is certainly very high, going, I believe, up to 10^6 volts per centimetre, and for this reason I am inclined to favour the hypothesis of increased electric strength rather than that of increased permittivity.

The "discrepancy" which Professor Thompson finds in the curves is really due to his neglecting to allow for the correcting factor "f," that is to say, he simply divides the breakdown voltage by the spark length without allowing for uneven distribution of electrostatic flux. If this be allowed for I think he will find that the figures agree all right.

In answer to Mr. Campbell, I am afraid that I have no accurate data as to how the permittivity of air is affected by the pressure. I believe,

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Mr. Watson.

however, any alteration which may exist is very slight, certainly I have never found that the air pressure has had any effect (beyond that of stopping breakdown) on any of my high-tension voltmeters, the calibration of which has always seemed to be independent of the air pressure.

In regard to the air condensers which gave trouble by leakage, a thin layer of paraffin wax on the plates was found to improve matters a great deal, although it did not entirely stop leakage. It would not, however, have been much use for my purpose, as the capacity of the condenser would have been liable to vary owing to the distribution of charge between the wax and the air being disturbed by leakage in one or other of them.

Professor Marchant suggests that possibly the breakdown of the condensers was due to the continuous electric stress, and hints that it might possibly not have occurred with alternating current. It must be borne in mind, however, that the stress on these condensers was not wholly continuous, but that at each spark they were subjected to high-frequency oscillations of the order of several million per second, and these would probably do more harm than a steady sustained stress of equal magnitude.

I do not see the force of Mr. Lustgarten's view that resonance is the explanation of the occurrence of a point of inflexion in the spark-length voltage curves for small spheres. What does he think forms the resonant circuit, and why should it only occur at one voltage? I presume that he keeps his frequency constant throughout any given test, and merely increases the excitation of his alternator in order to bring up his pressure in the same way that I did. In that case, if resonance were to occur at all, it would occur throughout the entire test and not at one point only; but what has resonance to do with the appearance of a point glow? Further, I have obtained points of inflexion with direct current, although, generally speaking, when using an influence machine it is not possible to carry the curve far along the upward rise owing to the amount of power required. In some former tests of mine, when using an influence machine more powerful than the present one, the upward bend of the curve and production of the corona were frequently observed. The fact that proximity to the transformer affected the point of appearance of the corona is easily accounted for by considering that in the region of this point the conditions are necessarily somewhat unstable, and therefore readily influenced by any disturbing element, such as ultra-violet radiations, which are copiously produced by all brush discharges even when the latter are scarcely visible to the eye. That ultra-violet light has an important disturbing effect was pointed out by Hertz, and has long been recognised. The use of shields also, by altering the distribution of electrostatic stress, might certainly be expected to influence the shape of the curve. As for the non-appearance of the "kink" in Algermissen and Heydweiller's results, this is simply due to the fact that they did not carry the voltage high enough. It is not stated in my

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Mr. Watson.

paper that 38·85 k.v. per centimetre could be taken as representing the electric strength of air under all conditions and for all sizes of electrodes. It is given as the value obtained with spheres 1 in. in diameter, but I cannot think it is ever as low as 30 to 33. Ryan's tests on wires, for instance, never give values much below 40 k.v. per centimetre. It was not possible to obtain consistent results for needle points under pressure, as the distance apart was too small, but the voltage required for a given gap appeared to increase very nearly in proportion to the pressure. Mr. Lustgarten is mistaken in saying that I referred to a value of 3 k.v. as being the minimum voltage required to produce a spark in air. What I stated was that although for high voltages the curves radiated from about that amount, yet on carrying the pressures lower they were found to bend round to a much lower value. I quite agree with Mr. Lustgarten that until the papilla stage is established the shape of the curves for a pair of spheres is practically represented by Dr. Russell's formula :—

$$R = \frac{v}{x} f,$$

and also that as the sparking distance increases the papilla becomes more nearly a true point discharge. In fact, as I have pointed out, this is the explanation of the occurrence of "kinks," or points of inflexion.

The President.

The President: It now only remains for us to pass a vote of thanks, which I am sure will be a hearty one, to the author for his very useful paper. He has worked hard on the subject and made himself a master of it; and I am quite sure that the information he has given us to-night will find practical engineering applications in many directions before very long.

The resolution of thanks was carried by acclamation.

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THE KAPP-HOPKINSON TEST ON A SINGLE DIRECT-CURRENT MACHINE.

By Dr. W. Lulofs.

(*Received from the* Birmingham Local Section *October* 1, 1908, *and read at Birmingham on January* 13, 1909.)

The Kapp-Hopkinson, or circulation-of-power test, is the most accurate method for finding the efficiency of two similar machines. Though the actual test is too well known to need explanation, its history may prove of interest.

In 1886 Major Cardew applied the following method for measuring the efficiency of direct-current machines. For this test three machines are necessary, preferably differing in output by the amount of power lost in each. The largest machine B supplied current to the medium-sized machine C, which drove by mechanical transmission through belting or direct coupling the smallest machine D, so that as near as possible full-load condition of C and D was obtained. The electrical power supplied to C and taken from D was measured, and the ratio of the two is the combined efficiency of C and D, and the square root of this ratio is the efficiency of each machine (see Fig. 1).

Dr. Hopkinson improved this method in 1888. The two machines, which in this case must be similar, are mechanically coupled. A pulley mounted upon this coupling takes the belt through which the power, necessary to run the machine light, is supplied. This power was measured by a Hefner-Alteneck dynamometer. By making the excitation of machine B weaker and of C stronger, B begins to act as motor; and C, as generator, supplies current to B. The circulating current is measured in ammeter A (see Fig. 2). The accuracy of this method is undoubtedly greater than that of the direct method where the whole of the power is measured. The loss is, in the first case, obtained as the difference of two large amounts; in the second case, the loss itself is measured. The loss, however, is measured in mechanical power with an apparatus which may have an error of 10 per cent. The rigging-up of the experiment is troublesome, and the test is made by means of two totally different sets of measuring instruments, which are not directly comparable with each other.

In 1890 Dr. G. Kapp proposed the following improvements. He supplies the loss of the two machines under test as electrical energy. A small dynamo suffices to keep a couple of large machines working

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at full load. The three machines are either put in series (in this case a battery can often be used) or in parallel (Fig. 3).

In the first case the auxiliary machine must be of low voltage, and

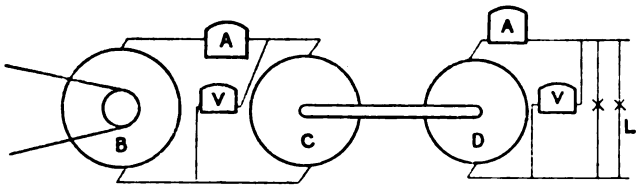

FIG. 1.

capable of carrying the full circulating current; in the second case it must be of the same voltage as the other two machines, but only need give a small current. In this form the circulation-of-power test has

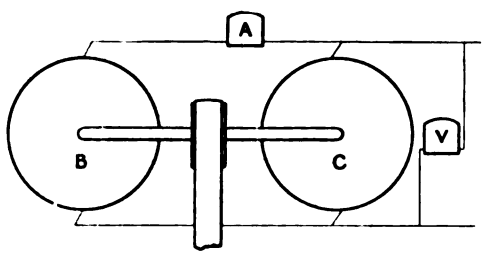

FIG. 2.

been generally adopted, not only for direct-current machines, but also for alternators and transformers. For all these tests two similar machines are necessary, and the efficiency arrived at is only accurate

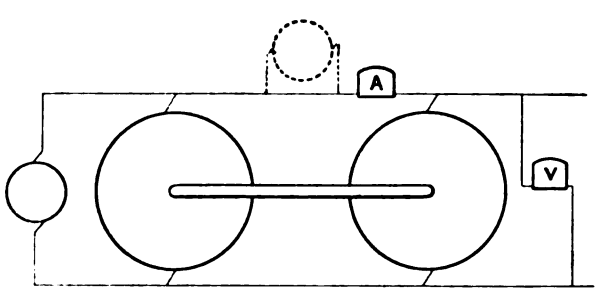

FIG. 3.

when the assumption holds good that the two machines have exactly the same efficiency.

For these reasons it has been attempted to obtain circulation of

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power, using only one machine. This has the advantage of simpler connections in general, more reliable results (because the efficiency is found in one machine only), and the possibility of carrying out the test when only one machine is available.

For alternators, a method originally suggested by Mordey, and recently improved by Behrend,* may be accepted as a solution, whilst Gustrin† likewise modified Dr. Sumpner's transformer efficiency test. In the case of direct-current machines, however, no successful attempts seem to have been made in this respect.

Whilst I was writing this paper, it appeared that A. Kolben was working on the same subject quite independently of me.‡ The method he suggests, however, is not correct, as I explained in my letter published in the same paper.§

The object of the following pages is to point out how the Kapp-Hopkinson test may be adapted on a single lapwound direct-current machine only, providing it is not supplied with Mordey equalising connections.

The connections need not be more complicated than in the ordinary test on two machines, and it has the great advantage that the efficiency of a machine can be tested *in situ*. The test as described was carried out on a 4-pole machine, but it may be understood that the principle of this test holds equally good for any machine having more than four poles. For a 6-pole machine—in fact, for all machines whose number of poles contains three—the test becomes a little more complicated, but is quite possible notwithstanding.

The principle is as follows: The two positive as well as the two negative brushes are disconnected, and two ammeters, A_1 and A_2, of equal range inserted in, say, the two negative leads (see Fig. 4), whilst the positive brushes are short-circuited through an ammeter A_3. Should now the exciting current of the two south poles so be altered that the excitation of S_{A_1} is strengthened by the same amount as that of S_{B_1} is weakened, then a difference of potential must be obtained between the two positive brushes when the armature rotates. As S_{A_1} is strengthened by the same amount as S_{B_1} is weakened, the two south poles may be considered to have retained their former strength, and to have superposed over them a field dependent on the magnitude of this alteration, and in the direction S_{A_1}, S_{B_1}.

The difference of potential so obtained between the positive brushes 1 and 2 will give rise to a current which flows in the two halves of the armature, and from Fig. 5 it is seen that this current flows down under S_{A_1}, up under S_{B_1}, and mixed up and down under N_{A_1} and N_{B_1}.

The armature ampere-turns produce a field which lies in the direction N_{B_1}, N_{A_1}, so an alteration of S_{A_1}, S_{B_1} in the way described inevitably involves an alteration of the north poles, strengthen-

* *Electrical World and Engineer*, p. 715 (1903).
† *Electrotechnische Zeitschrift*, 1907.
‡ *Electrical Engineer*, March 6, 1908.
§ See also *Electrical Engineer* and *Electrician*, March 27, 1908. Ibid., March 13th.

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ing (Fig. 5) N_{B_1} by the same amount as N_{A_1} is weakened. The armature, however, revolves in this field, built up by its own ampere-turns, and for this reason a potential difference must be created

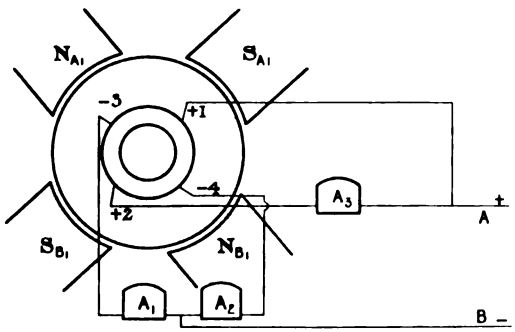

FIG. 4.

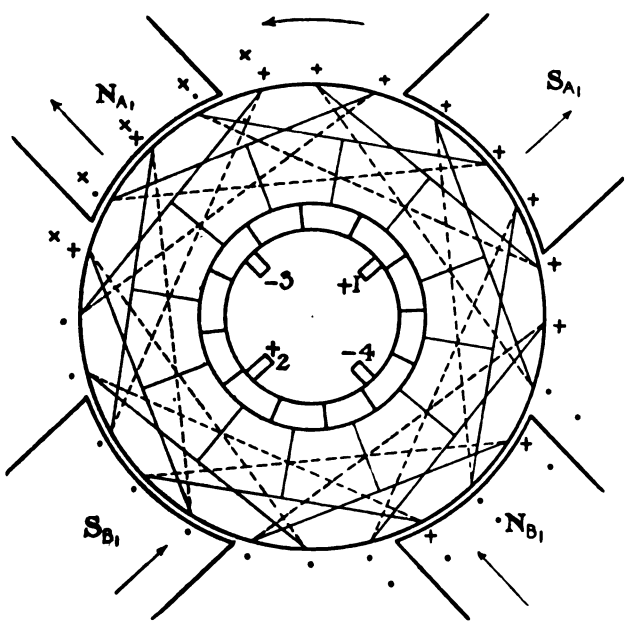

FIG. 5.

between the two negative brushes, tending the current to flow downwards under N_{A_1}, upwards under N_{B_1}, and mixed up and down under S_{A_1} and S_{B_1}. These armature ampere-turns in their turn excite a field over the two south poles in the direction S^{A_1}, S^{B_1};

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that is, in the opposite direction to the alteration originally produced, or, in short :—

The armature reaction of a lapwound machine will tend to prevent a circulating current from flowing from one brush to the other of equal potential. To this behaviour of the armature I will refer again later on.

In order to enable a circulating current to flow, say, from positive brush 1 to positive brush 2, the armature reaction in direction N_{B_1}, N_{A_1} must be counterbalanced. This can easily be done in the same way as the original alteration of the south pole fields is obtained. This circulating current, which now leaves the positive brush under S_{B_1}, flows through the ammeter A_3, and is measured by same, and, flowing back to the armature in positive brush under S_{A_1}, divides equally in the two halves of the armature. The magnitude of this current is dependent on the magnitude of alteration given to S_{A_1}, S_{B_1}, and the

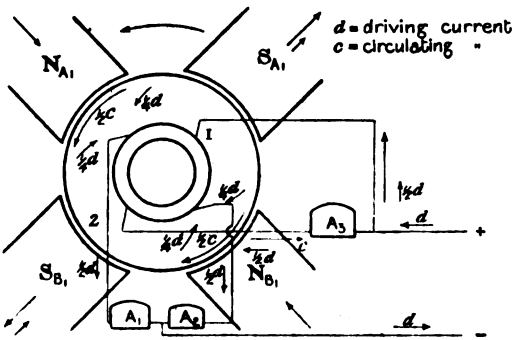

FIG. 6.

armature reaction produced by itself. As already explained, the armature reaction gives rise to a current leaving the armature at, say, brush 4, flowing through ammeters A_1 and A_2, back into armature through brush 3, and counteracts the alteration given to S_{A_1}, S_{B_1}. This second circulating current is, therefore, a disturbing element, and must be done away with in the way already explained, and the two ammeters A_1 and A_2 showing no deflection indicate that this condition is obtained.

In order to run the armature at its normal speed it is not necessary to drive it mechanically. In connecting the two armature terminals as usual to the normal voltage supply, and giving the fields the normal excitation, the machine can be started up in the ordinary way as motor running light, and its speed can be adjusted by the voltage impressed on field or armature.

A_1, A_2, and A_3 will all read half the running light current, and the sum of A_1 and A_2 multiplied by the voltage impressed gives the power

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which the machine consumes running light.* The circulating current can now be obtained in the above-mentioned way, and A_3 will read double the value of the circulating current in the actual armature bars + or — half the running light current, whereas A_1 and A_2 are kept indicating alike currents by totally counterbalancing the armature reaction. Hence the current divides in the armature as shown in sketch (Fig. 6). That part of the armature under south pole S_{A_1} carries current $\frac{1}{2}c + \frac{1}{2}d$, and working under the stronger pole acts, therefore, as the motoring half. The opposite part carries $\frac{1}{2}c - \frac{1}{2}d$, *i.e.*, the smaller current, and acting under the smaller field works as dynamo.

How to Alter the Fields.—The most accurate way to strengthen one pole as much as the other is weakened is the following: If for a 4-pole machine half the field voltage is supplied to *a a* (Fig. 7), and the inter-

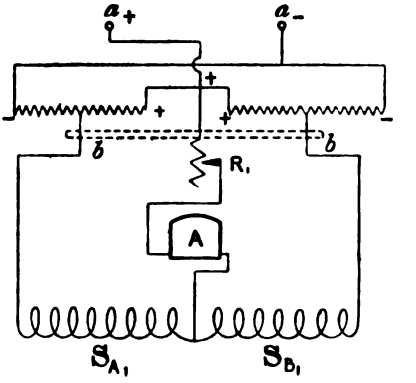

FIG. 7.

locked pointers *b b* of two equal main-current regulators stand in the middle positions, the current through S_{A_1} is equal to that through S_{B_1} and of the normal value. By moving the pointers *b* to the right, however, the voltage over S_{B_1} is raised by exactly the same amount as that by which the voltage over S_{A_1} is weakened, and *vice versâ*, the result being that by moving *b* the ratio between S_{A_1} and S_{B_1} can be varied *ad libitum*, keeping the total current constant. As the field excitation will certainly be over the knee of the excitation curve the weaker poles will be weakened to a slightly greater extent than the stronger poles are strengthened. This is, however, of no consequence, because a relative small displacement of *b* is necessary to obtain the full circulating current; anyhow, if the impressed E.M.F. and the speed are kept constant the total field strength must remain the same. A fine adjustment for the total field current is therefore necessary, and can be made by altering R_1. A similar arrangement to change the relative strength

* The field watts are not considered.

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TABLE I.

Speed.	Mean Load Current.	Driving Current.	Field Current in Amperes in each Circuit.	Machine Volts kept Constant.	Field Volts.	Armature Loss in Watts, including Half-brush and Distribution Loss.	Armature Loss in Watts, excluding Half-brush and Distribution Loss.
630	26·0	4·76	2·3	220	110	1,048	1,027
630	33·9	4·95	2·3	220	110	1,089	1,042
630	52·0	5·40	2·3	220	110	1,188	1,102
630	60·6	5·70	2·3	220	110	1,252	1,141
630	82·0	6·50	2·3	220	110	1,430	1,255
630	102·3	7·29	2·3	220	110	1,600	1,400
630	111·1	7·85	2·3	220	110	1,725	1,470

Half-brush and Distortion Loss in Watts.	Total Armature Loss in Watts.	Total Field Loss in Watts.	Total Loss in Watts.	Apparent Load in Watts.	Per Cent. Loss, Total.	Efficiency in Per Cent.
21	1,069	507	1,576	5,710	27·60	72·4
47	1,136	507	1,643	7,450	22·10	77·9
86	1,274	507	1,781	11,420	15·60	84·4
111	1,363	507	1,870	13,350	14·00	86·0
175	1,605	507	2,113	18,000	11·70	88·3
200	1,800	507	2,307	22,500	10·25	89·5
255	1,980	507	2,487	24,400	10·20	89·8

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of the two poles of opposite polarity, so as to counterbalance the armature reaction due to the circulating current, must be made.

Actual Test.—After having made arrangements for changing the relative strength of the poles, the machine is run up as motor in the usual way. Allow a certain circulating current to flow in the way described, and read the value which A_3 will give if half the driving current is added on to it. This value gives the mean load current. The driving current is obtained from ammeters A_1 and A_2, each reading half this amount, and arranged to indicate equal currents by a suitable out-of-balance (in this

TABLE II.

Armature Current.	Armature Resistance Hot, excluding Brushes.	Watt Loss in Armature Winding.	Armature Light-running Driving Current.	Armature Loss in Watts, excluding Brush and Distribution Loss.
10	0·038	3·8	4·55	1,003·8
20	0·038	15·3	—	1,015·2
30	0·038	34·2	{ at 220 volts } { = 1,000 watts }	1,034·2
40	0·038	60·8	—	1,060·8
50	0·038	95·0	—	1,095·0
60	0·038	132·0	—	1,137·0
70	0·038	186·0	—	1,186·0
80	0·038	243·0	—	1,243·0
90	0·038	308·0	—	1,308·0
100	0·038	380·0	—	1,380·0
110	0·038	460·0	—	1,460·0
120	0·038	548·0	—	1,548·0

case) of the two north poles N_{A_1}, N_{B_1}. In this way the armature reaction is counterbalanced, so that only a circulating current can flow between brushes 1 and 2. The driving current d multiplied by the E.M.F., under which pressure this current flows, represents obviously the power which the machine consumes running under these conditions. A test was carried out on a 4-pole lapwound machine manufactured by Messrs. Allen & Son, 230 volts, 120 amperes, and Table I. shows the figures thus obtained. In order to calculate the true efficiency of this machine under ordinary working conditions from the figures obtained (Table I., columns 3 and 5, curve I.) some correc-

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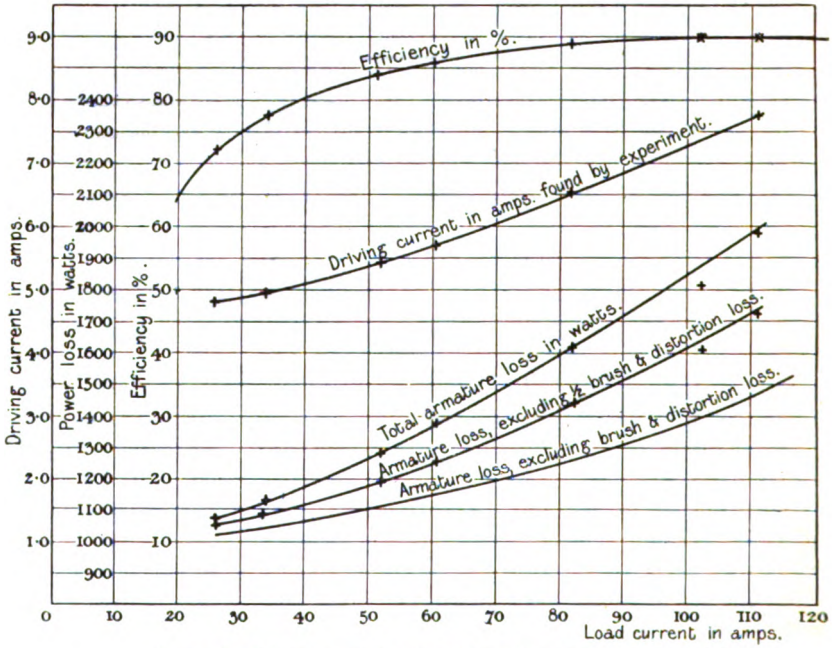
tions must be made. Two losses are not expressed in these results, namely, brushes 3 and 4 carry no circulating current; secondly, the poles N_{A_1} and N_{B_1} are not distorted by the armature current flowing under them, so that to the losses (Table I., column 7) these have to be added separately. The calculation of these losses is very simple. The watts required to drive the load current through the armature only (excluding brushes) are calculated for all values of this current, the armature resistance being known to be 0·038 at maximum temperature * (see Table II., curve V.).



Curve I.—Driving current in amperes found by experiment.
" II.—Armature loss, excluding ½ brush and distortion loss.
" III.—Total armature loss in watts.
" IV.—Efficiency in per cent.
" V.—Armature loss, excluding brush and distortion loss.

The watts consumed with the machine running at all values of load current, excluding total loss in brushes, and that due to distortion of the fields by the armature current, can now be obtained by adding results. Table II., column 3 gives the running light losses, which amount to 1,000 watts. Column 5 gives this total value.

Table I., column 8, gives these same values for the load currents actually used in test. Column 9 is the difference of the two, which

* The efficiency test was not started before the machine had reached its maximum temperature, and the mechanical pressure on brushes 1 and 2 was adjusted to equal the pressure on brushes 3 and 4.

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obviously is the required half-brush and distortion loss. These values, added to figures tabulated in column 7, give the total armature loss (column 10).

Column 11 represents the field loss, which has to be added to the armature loss to obtain the total loss in the machine. The three remaining columns speak for themselves. An error which cannot be corrected is that due to the rotation of the armature in a field superposed over that of the two poles N_{A_1} and N_{B_1}, but this certainly does not cause an appreciable error.

There also is (due to this field) a slight side-pull on the shaft which might affect the friction losses, but as the friction losses do not depend on the bearing pressure unless the latter exceeds about 550 lbs. per

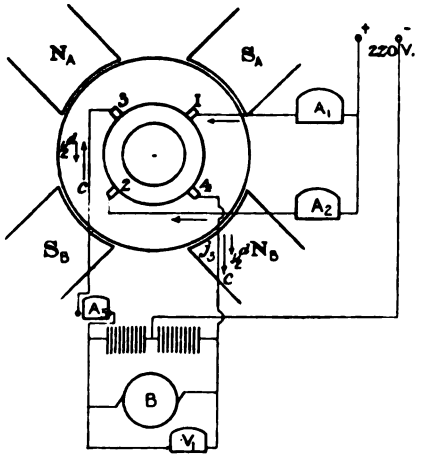

FIG. 8.

square inch, also this matter is of no consequence, especially if care is taken that the stronger field is above.

The above-described test is simple in its carrying out, and the corrections that must be made to obtain the required result are very easy. In many cases the test can be made with the use of an auxiliary machine or battery of low voltage, capable of carrying half the full-load current (Fig. 8).

A difference of potential between brushes 3 and 4 is obtained by means of the low-voltage machine B, and by counterbalancing exactly the armature reaction caused by the current tending to flow by the impressed low voltage the same conditions can be obtained as in the test previously described. A_1 and A_2 again read the same value—namely, half the driving current, and A_3 the circulating current—half the driving current. This method of proceeding makes it possible to separate the power required for driving the motor from the circulating power, and the rise of current indicated by ammeters A_1 and A_2 is

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directly a measure of the loss due to the distortion of one pole pair by the circulating current. The total field strength of N_A and N_B is not affected by the tendency of the circulating-current-armature-reaction, which has the direction S_A, S_B, to weaken one and strengthen the other. This effect, however, is totally counterbalanced in the ordinary way already described, and this is obtained as soon as A_1 and A_2 read the same value. Twice the rise of current indicated by A_1 has to be added to twice that indicated by A_1, and then multiplied by the impressed voltage. To this must be added the power necessary to produce the circulating current; and finally, in addition to this, the power required to send the loaded current through the brushes 1 and 2 equal to $I_3(V_1 - I_3 R)$, R being the resistance of the armature only. This method has the advantage that only one pair of poles need be relatively changed, and, secondly, the watt loss in the brushes and

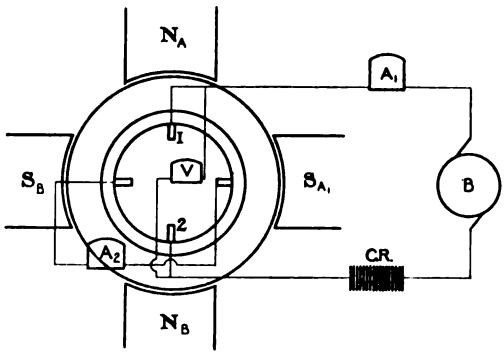

FIG. 9.

increased hysteresis and eddy-current loss due to field distortion are easily separated.

This, however, only holds good when the armature is exactly in the centre. It is clear that the actual pole strength is not affected by the circulating current, as the armature reaction is entirely counterbalanced. The circulating current, therefore, cannot exert a driving force. In case the armature is not concentric or one north or south pole stronger than the other, the above test may lead to very inaccurate results.* As the machine on which I worked had the above-mentioned defect, it was impossible to obtain any reliable results in this way.

In both the suggested methods corrections are necessary, and some losses occurring under the usual running conditions do not appear in the test itself, although they are easily allowed for in the efficiency test by calculating their magnitude; for the heat test, a correction cannot be made.

I therefore propose the following test (Fig. 9) :—

* It is also very essential that the brushes should be in exactly the neutral line.

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To send from auxiliary machine B a current, say, in at brush 1 and out at brush 2. Ammeter A_1 measures this current, and by means of the carbon rheostat C R or changing the pressure of B, it is adjusted to half the full-load current. The poles are normally excited, but current A_1 exerts no torque. By strengthening N_A, weakening N_B, and at the same time counterbalancing the armature reaction of A_1 so far till A_2 also reads half the full-load current, the full-load running conditions are obtained, and the product of volts V and amperes A_1 gives at once the full-load loss which occurs in the machine.

The only difference to the load condition is that in every other armature bar double the current flows, while the other bars are free from current. These big current values cannot hurt the machine, as the bars carrying double load and no load continually change conditions. As the general direction of this current is down under N_{A_1}, up under N_{B_1}, down under S_{A_1}, up under S_{B_1}, only a torque can be

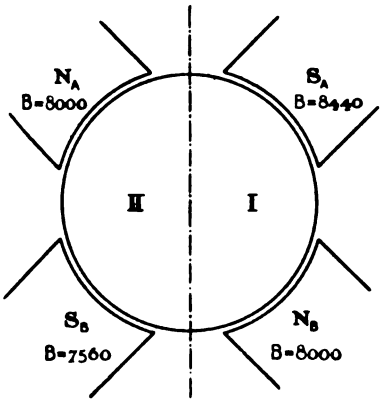

FIG. 10.

exerted in changing the pole strength of two opposite poles, in this case N_A, N_B.

The values of the efficiency obtained by both methods tally fairly well for full-load condition.

That the second method shows greater efficiency on small load is probably due to the fact that the machine in question was taken to pieces between the two tests for alterations; the brushes were shifted, and probably the second test has been carried out with a different brush position. It is well-known that the power required for running a motor light is, especially for machines without commutating poles, largely dependent on the brush position. This is due to the fact that more power is used for the commutation when the brushes stand in a less favourable position. Probably the brushes were in a less favourable position for full load during the second test, and this would also account for the higher efficiency obtained under light load condition.

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Results obtained by the last described method :—

TABLE A.

Speed.	Current A_1.	Current A_2.	Volts V.	Total Armature Loss.	Field Loss.
630	20·0	20·00	50·0	1,004	507
630	29·5	29·75	40·3	1,190	507
630	40·0	40·00	36·6	1,462	507
630	44·5	43·00	37·2	1,655	507
630	50·0	50·00	37·8	1,890	507
630	55·0	54·75	38·1	2,095	507
630	60·0	60·00	40·0	2,400	507

Total Loss.	Apparent Load.	Per Cent. Loss.	Efficiency in per Cent.
1,511	8,800	17·20	82·80
1,697	12,980	13·10	86·90
1,969	17,600	11·20	88·80
2,162	19,600	11·05	88·95
2,397	22,000	10·90	89·10
2,603	24,200	10·78	89·22
2,907	26,400	11·00	89·00

The fact that the results of the above two tests tally fairly well with each other for the particular machine in question is, however, little proof that the tests proposed by me are absolutely reliable.

Practice can only decide this, and not before a great number of tests on various machines are taken can a decision be arrived at. An approximate calculation of the difference in iron loss which is obtained in the test described may justify, however, my assumption that these, under ordinary circumstances, can never reach an appreciable value.

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Approximate Calculation of the Magnitude of Difference in the Iron Loss. First Method.—From Figs. 5 and 6 it can be seen that the only alteration in the field strength is that S_A is increased, S_B decreased, whereas the poles N_A and N_B remain unaltered. This alteration of the south poles must be carried on until the voltage between brushes 1 and 2 (due to this difference in polarity of S_A and S_B, which we will call a superposed field $S_B \longrightarrow S_A$) reaches such a value that the full-load current flows from brush 1 to brush 2.

The armature resistance (as measured from brushes 1 to 2) equals 0·1514 ω, so that the necessary voltage for full load amounts to $0{\cdot}1514 \times 60 = 9{\cdot}1$ volts, whereas the volt drop on the brushes 1 and 2 at the same current was found to be about 3 volts.

The total is, therefore, 12·1 volts or 5·5 per cent. of the machine pressure, so that the necessary superposed field must be 5·5 per cent. of the total.

The total field was found to be 3·3 megalines, and B about 8,000, so that the inductance of the superposed field $B_s = 440$ lines.

Fig. 10 shows the altered field condition.

To obtain an approximate estimate of the additional iron losses due to the presence of the superposed field, the armature can be divided into two halves.

Part I. under poles S_A, N_B performs a cycle of magnetic change between the limits + 8,000 and − 8,440. The hysteresis loss for this part will be about the same as if the cycle took place between the limits + 8,220 and − 8,220.*

For Part II. the magnetic change may be calculated to be between the limits + 7,780 and − 7,780. The same reasoning holds good for the eddy-current loss. The increase in iron loss in watts can now be found from the formulæ :—

$$p\,(\eta\, n\, B^{1\cdot6} + \beta\, n^2\, B^2)10^{-4} - \left\{\tfrac{1}{2}\,p\,(\eta\, n\, B_1^{1\cdot6} + \beta\, n^2\, B_1^2) + \tfrac{1}{2}\,p\,(\eta\, n\, B_2^{1\cdot6} + \beta\, n^2\, B_2^2\right\} 10^{-4}.$$

η taken at 0·0018.

β at $5{\cdot}10^{-7}$.

$n = \dfrac{630{\cdot}2}{60} = 21.$

p = volume of armature iron in $d\ M^3 = 13$.

$B = 8{,}000.$

$B_1 = 8{,}220.$

$B_2 = 7{,}780.$

This worked out gives a value of 0·026 Joules, which lies far beyond the accuracy of the instruments used.

The extra pull on the shaft due to the superposed field is :—

$$\frac{A\,B_1^2}{8\,\pi} - \frac{A\,B_2^2}{8\,\pi}$$

* See Benischke, *Die Grundgesetze der Wechselstromtechnik*, p. 77.

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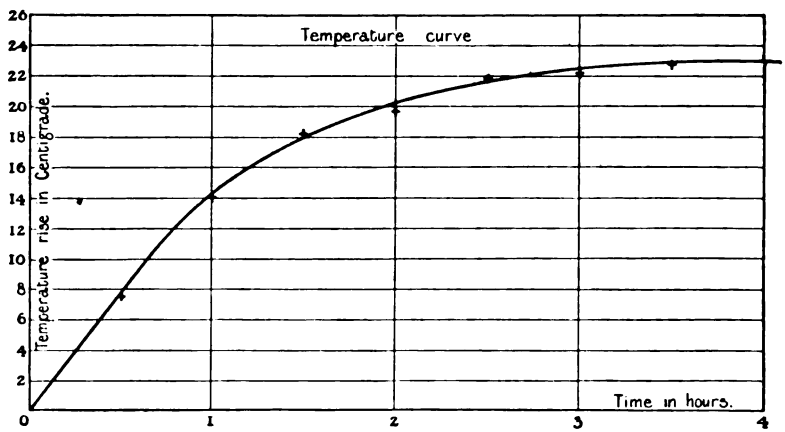
(in which A is the area of a pole = 418 cm.²), which amounts to 119 kilogrammes.

It is evident that this side-pull cannot influence the friction loss to any extent, as the armature weight is about 300 kilogrammes.

Second Method.—A pressure of 40 volts is necessary to drive the motor current through the armature at full-load condition (see Table A, column 4), of which 12·1 volts are taken up in ohmic drop—the back E.M.F. is for this reason 27·9 volts or 12·65 per cent. The superposed motor field is therefore 1,030 lines. The actual field distribution is therefore—

$$B_{NA} = 9{,}030.$$
$$B_{NB} = 6{,}970.$$
$$B_{SA} = 7{,}560.$$
$$B_{SB} = 8{,}440.$$

Working in the same way as for Method 1, the additional iron loss is found to be 0·52 Joules, whereas the side-pull on the shaft



Curve VI.—Temperature curve.

amounts to 560 kilogrammes. The pull in direction S_A, S_B is 119 kilogrammes, so that the resultant is 570 kilogrammes, which in many cases is about the side-pull on the armature when the machine is belt-driven.

Heat Test.—The heat test on a lapwound direct-current machine can be carried out on the same lines, and by measuring the armature resistance at intervals its temperature can be found by making use of the well-known formula—

$$R_T = R_{15}(1 + \alpha t),$$

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in which—

R_T = resistance at the temperature which has to be found.
R_{15} = same at 15°.
a = temperature coefficient of copper at 15° = 0·004.
t = temperature to be measured.

A correction for the temperature which must be slightly lower than the true values cannot be made.

I tested the actual difference, first submitting the machine to the usual Kapp-Hopkinson test, and found a maximum temperature rise in the armature of 24·5, and secondly, to above test. Curve VI. shows the temperature rise thus obtained, which shows the difference is by no means appreciable (Table III.).

TABLE III.

Time in Hours.	Resistance in Ohms.	Temperature Rise in Deg. C.
0	0·1382	0·0
0½	0·1429	6·7
1	0·1460	14·1
1½	0·1482	18·1
2	0·1491	19·7
2½	0·1503	21·9
3	0·1510	23·2
4	0·1514	23·9
4½	0·1513	23·7

Before closing, a few words may be said on the nature of the armature reaction in a lapwound machine, as its particular character is not always entirely realised, which often leads to faulty conclusions arrived at even by well-known writers. For example, A. Thomälen writes in his book "Lehrbuch der Electrotechnik," p. 137, if the pole-pairs of a lapwound machine are not of equal strength the E.M.F.'s induced in the armature circuits are also unequal; for this reason the current divides unequally in the armature. In Fig. 11, for example, the induced E.M.F. in the two upper circuits may be $E_1 = 115$ volts, and due to the uneven pole-strength the induced E.M.F. in the two lower circuits may be $E_2 = 114$ volts. The ohmic resistance of each two circuits in series may be $w' = 0·05$ ohm. What is the current in each armature circuit when the total current is 100 amperes?

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As the terminal voltage of both circuits is equal, we can write :—

$$E_1 - i_1 w' = E_2 - i_2' w' = e.$$
$$115 - i_1 0{\cdot}05 = 114 - i_2 0{\cdot}05.$$
$$1 = (i_1 - i_2) 0{\cdot}05.$$
$$i_1 - i_2 = 20.$$

In case the total current is 100 amperes—

$$i_1 = 60 \text{ amperes.}$$
$$i_2 = 40 \text{ amperes.}$$

It is quite clear that in this calculation the equalising effect of the armature reaction is overlooked.

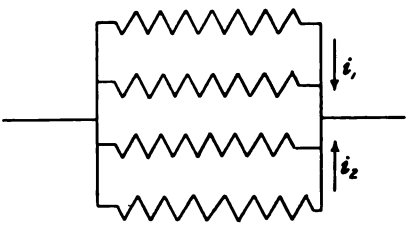

FIG. 11.

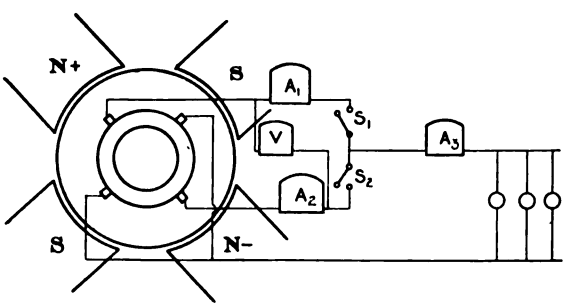

FIG. 12.

Say that the armature of a 4-pole lapwound machine is eccentric and the air-gap under one north pole is smaller than under the other, thus making the former stronger and the latter weaker, a pressure difference between the two corresponding brushes of the same polarity occurs, and a circulating current tends to flow. The armature reaction due to this current weakens one south pole and strengthens the other; this causes a difference of polarity between the other two brushes, and a current will tend to flow whose magnetic action opposes and partly wipes out the original difference in strength between the two north poles. This equalising effect depends mainly on the difference in strength of the other two poles of the saturation of the field, and the

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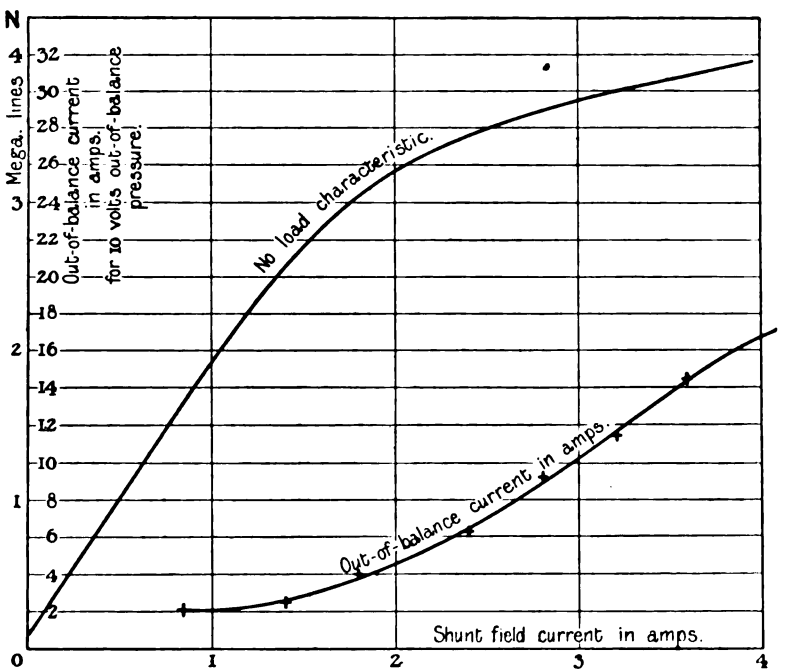
ampere-turns on the armature, so that a projection of the magnitude of the circulating current is impossible. As an illustration, I made the following test :—

Strengthening one north pole and weakening the other, a potential difference of 10 volts was obtained between the two positive brushes at a certain excitation. After having closed switch S_1 and S_2 (see Fig. 12), a load was put on the machine, and the difference of the ammeters A_1 and A_2 gives the out-of-balance current. The results are tabulated below (see Table V.). A second point I investigated was



Curve VII.—Out-of-balance current in amperes.

how the out-of-balance current is dependent on the saturation of the fields, keeping the pressure difference between the two brushes equal at various excitations. Curve VII. shows that the out-of-balance current increases readily when the poles get saturated. This, however, does not represent the actual working condition of the machine. As soon as the poles get saturated the actual difference due to eccentricity of the armature or to any other reason* will diminish rapidly.

* In case the out-of-balance voltage between two brushes of the same polarity is due to one pole-piece being porous, the same will not diminish with increase of the field strength.

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TABLE IV.

Out-of-Balance Volts.	Field Current.	Out-of-Balance Current in Amperes.
10	0·84	2·0
10	1·40	2·4
10	1·80	3·7
10	2·40	6·3
10	2·80	9·2
10	3·20	11·2
10	3·60	14·4
10	4·10	17·2

TABLE V.

Field Current in Amperes.	Current A_1 in Amperes.	Current A_2 in Amperes.
1·5	5·0	3·0
1·5	10·9	8·7
1·5	20·5	19·0
1·5	27·9	26·2
1·5	30·9	29·5
1·5	34·0	33·0
1·5	41·9	40·5
1·5	46·1	44·5
1·5	50·5	48·0
1·5	55·0	52·0
1·5	59·5	55·5

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These two facts explain why in a lapwound machine the current divides fairly equally in the armature at all magnitudes of excitation even when the armature is appreciably out of centre.

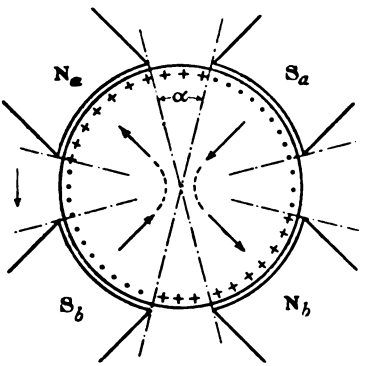

FIG. 13.

This equalising effect of a lapwound armature is not only dependent on the condition of the field, it is far more complicated, and a closer study of this phenomenon should be of great value to manufacturers.

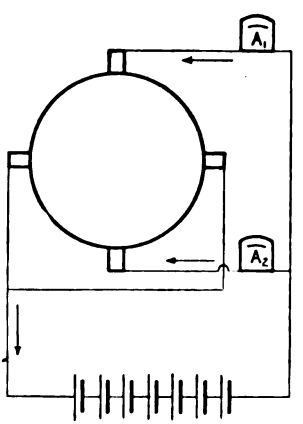

FIG. 14.

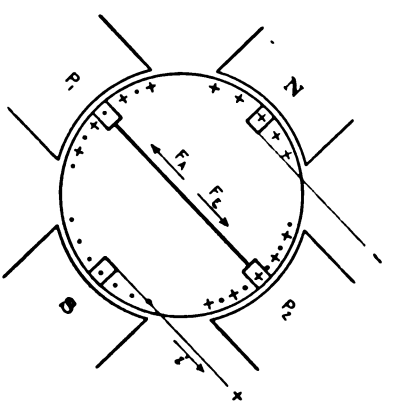

FIG. 15.

It is easy to see that the brush position and direction of rotation are of great influence.

Let Fig. 13 represent a 4-pole lapwound machine, running as motor. Say the brushes are shifted backward over angle α, the armature reac-

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tion demagnetises all four poles. If the air-space under N_a and S_b is smaller than that under S_a and N_b, N_a will be weaker than N_b, S_b weaker than S_a, and a superposed field will exist in which—

N_a is a south pole, N_b a north pole,
S_b „ „ S_a „ „

Hence the lag in the brush position works favourably on the uneven field distribution due to eccentricity of the armature.

I am unable now to go further into this subject, which seems of the greatest importance, and well worth the attention of the designing engineer.

The effect of the direction of rotation on the even distribution of the armature current can clearly be seen from the following Table VI.

TABLE VI.

Current A_1 in Amperes.	Current A_2 in Amperes.	Out-of-Bafance Current in per Cent. of A_2.	Brush Position.	Direction of Rotation.
50·0	12·0	317·00	Neutral	Standing
25·8	29·6	12·20	„	Clockwise
31·6	36·4	13·20	Lagging	„
23·4	26·2	10·70	Leading	„
24·0	25·2	4·70	Neutral	Counter-clockwise
21·2	21·8	2·75	Leading	„
28·8	30·2	4·65	Lagging	„

The armature was driven by a motor, the field was unexcited, and the current was sent through the brushes as diagram Fig. 14 indicates.

A useful application of the armature reaction of a lapwound machine is a constant-current machine, which will be more efficient and easier to commutate than the Rosenberg machine. The useful generator field is not excited by a big armature current, but is separately or self-excited, and only in case the speed varies one way or the other will a balancing armature current flow through the short-circuited brushes. Fig. 15 may illustrate the working of the machine. Poles N and S are excited from the positive and negative mains, and a current will tend to flow as indicated. The armature current, however, excites a field in direction F_a, making P_2 north and P_1 south. This will result in a

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current which will flow down under P_2 and up under P_1, demagnetising the poles N and S almost completely.

By exciting P_2 and P_1 equal and opposite to F_A, however, a particular current i_1 can flow, whose armature reaction is equal to $F_a = F_f$. If now the speed goes up i_1 will tend to increase, F_a becomes bigger than F_f, and poles N and S are demagnetised accordingly. In case the speed goes down F_a becomes smaller and N and S are strengthened. I carried out some tests in this way, and am preparing a paper on this subject.

Discussion.

Dr. W. E. Sumpner.

Dr. W. E. Sumpner: It is very difficult for any one fully to appreciate or to criticise the method described until he has actually tried it and thoroughly understands its working. It looks complicated on paper, but I have no doubt it is a good method when one gets used to it. The test as applied by the author to a 4-pole machine is described as a single machine test, but might equally well be described as a test on two machines. Any multipolar machine can be regarded as a number of complete machines permanently coupled together electrically and mechanically.

Mr. Holden.

Mr. S. H. Holden: I shall be glad to have information as to whether the test will not be somewhat affected by the short-circuit currents between the segments under the brushes due to the weakening of one pole and the strengthening of the other. With regard to bearing friction, which Dr. Lulofs rightly says is small, I do not think that the difficulty is quite overcome by arranging that the pull caused should be upwards, because in that case the bearing friction will be less than under actual working conditions.

Dr. Kapp.

Dr. G. Kapp: I hope that some of the members present will be able to give the results of their experience with Mordey equalising connections. We have always understood from the text-books that it is dangerous to work the machines without these connections on account of the heavy circulating currents that would otherwise occur. If the author is right in his conclusions the equipotential connections might be dispensed with.

Mr. Gott.

Mr. A. E. Gott: The present paper is the fourth during the session on the testing of electrical machinery—a fact which emphasises the importance of the subject. I do not quite see how the test can be applied to machines having an odd number of pairs of poles, although the author considers that there is no difficulty. I would also point out that although dynamo designers make the shaft very rigid in order to resist side stress, yet in the test described it would appear that the weakened poles are all on one side of the armature, which is bound to produce stresses for which the machine is not designed, particularly in view of the shorter air-gaps incidental to some interpole machines.

Dr. Coales.

Dr. J. D. Coales: I have had the privilege of seeing many of the author's tests, and consider one of the most striking is that showing the inherent equalisation of the currents in the various armature circuits of

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Dr. Coales. a lap-wound machine, owing to the reactions of these currents. The paper leads to the conclusion that it is even more difficult to measure the resistance of an armature under normal running conditions than is generally supposed, at any rate in the case of a lap-wound machine. The method usually adopted when such a measurement is required is to send a current through the armature and to measure the resistance of the armature when running in one direction with the fields unexcited, and then again while it is running in the opposite direction. The mean of the two measurements is then supposed to give the true resistance, because the E.M.F. due to residual magnetism is then eliminated. The method leaves the reactions of the currents out of consideration, and these may considerably modify the distribution of current amongst the circuits, rendering the measurements quite unreliable.

Mr. Wigley. Mr. G. A. WIGLEY (*communicated*): The author is to be congratulated on having successfully solved a difficult problem, but, at the same time, the method does not admit of such universal commercial application as might at first sight appear. In the first place, it is obvious that a 2-pole machine cannot be tested in this manner. Secondly, the author states that the test may be carried out on a "lap-wound machine, provided it is not supplied with Mordey equalising connections"; and, thirdly, the method is not at all applicable to a series- or wave-wound machine; whereas the Kapp-Hopkinson test may be applied equally well to all machines, including compound-wound machines, provided that the series field turns on the motor are reversed.

Manufacturers generally employ wave-windings for small machines wherever possible, on account of the superior slot-space factor and the elimination of troubles due to unequal pole-strength, although sometimes the latter advantage is sacrificed by making the number of brush sets fitted equal to the number of poles, in order to reduce the length, and therefore the cost, of the commutator. Equalising rings are nearly always fitted to parallel or lap-wound armatures, especially now that the general use of special commutating poles has raised the sparking limit and made the heating limit relatively more important.

As the successful testing of electrical machines by the ingenious method carried out by Dr. Lulofs is of such importance, it will be gratifying indeed to learn that he has succeeded in applying his method in the above-mentioned cases, which in practice constitute so large a majority.

Dr. Lulofs. Dr. W. LULOFS (*in reply*): I do not deny that the method I have described is complicated, but I think it compares favourably with other complicated tests. I consider that the test will be particularly useful in cases where one machine only is available. Dr. Sumpner seems to disagree with my definition of a single machine. But my object was to show that the circulation-of-power test can be done on a single direct-current lap-wound machine only, this having the great advantage that no second similar machine is required for the test. I feel sure that designers have not paid enough attention to the fact that the circulating current in a lap-wound armature reacts in such a manner as to wipe out

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the cause which produces it. This effect is decreased with the saturation of the poles, as I have shown on page 167. It may therefore be advisable to design lap-wound machines with fields of moderate saturation, although in doing so the differences of pole-strength due to eccentricity of the armature, etc., will be increased. As to the effect on commutation due to the alteration of poles, this is a matter I cannot deal with straight away, but in any case it is a very small effect and not likely appreciably to alter the efficiency. Dr. Lulofs.

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FLYWHEEL LOAD EQUALISERS.

By J. S. PECK, Member.

(*Received from the* MANCHESTER LOCAL SECTION *January* 19, *and read at Manchester on February* 23, 1909.)

The flywheel has long been used as a load equaliser on steam engines, rolling mills, punch presses, etc., but its use in connection with an electrical machine as an equaliser of the load on a generating station is of comparatively recent origin. The use of the accumulator or storage battery for this service is common practice, and for certain conditions of operation it is admirably adapted, but for other conditions the flywheel equaliser is cheaper, more efficient, and in general better suited. The great advantage of the accumulator is that it can be built commercially for very large capacities, and can be used to carry peak loads, which may be of several minutes' or of several hours' duration, whereas the amount of energy which can be stored in even a large flywheel is comparatively small.* On the other hand, a flywheel may be brought up to speed in a few seconds, and may be made to give up its stored energy in the same time, while several hours are usually required for charging an accumulator, and it gives its best results when discharged at a correspondingly slow rate. It is thus evident that where the load fluctuations are extreme and of very short duration the flywheel equaliser is better suited, and that where the load fluctuations are more gradual and the peaks and hollows of long duration the flywheel equaliser is unsuited and the accumulator well adapted. An accumulator could be installed, of course, which would have sufficient capacity to handle fluctuations in load however violent, but one of enormous size would be required, since a very small percentage of its total stored energy can be given out in a few seconds' time, while 50 per cent. of the total stored energy of a flywheel can be discharged in an extremely short time.

As is well known, a flywheel can neither give up nor receive energy unless its speed be changed. The foot-pounds of energy stored in a flywheel are equal to $\frac{1}{2}$ M v^2, where M is the mass $\frac{\text{lbs.}}{32{\cdot}2}$ and V is the velocity in feet per second of a point at the end of the radius of gyration. If a flywheel of mass M be slowed down from velocity V to

* The total energy in a 10-ton flywheel running at a peripheral speed of 20,000 ft. per minute is about 750 k.w.-minutes, and as only approximately one-half this energy can be taken from the wheel economically, the amount available is but 375 k.w.-minutes = 750 k.w. for $\frac{1}{2}$ minute = 1,500 k.w. for $\frac{1}{4}$ minute, etc.

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velocity V_1 the energy given up is $\frac{1}{2} M (V^2 - V_1^2)$. From this it will be noted that the flywheel effect depends upon the peripheral speed and not on the revs. per minute. There is no object, therefore, in making the revs. per minute higher than necessary to give the maximum allowable peripheral speed on the flywheel, with a reasonable diameter, for when the maximum safe limit of peripheral speed has been reached any further increase in revs. per minute means a reduced diameter with a corresponding increase in the length of the flywheel. If the limiting speed of the flywheel is 20,000 ft. per minute, then a speed of 1,000 revs. per minute will give a wheel 6 ft. 4 in. in diameter, which is about as small as it is desirable to go for flywheels of any great weight.

The flywheel load equaliser consists essentially of an electrical

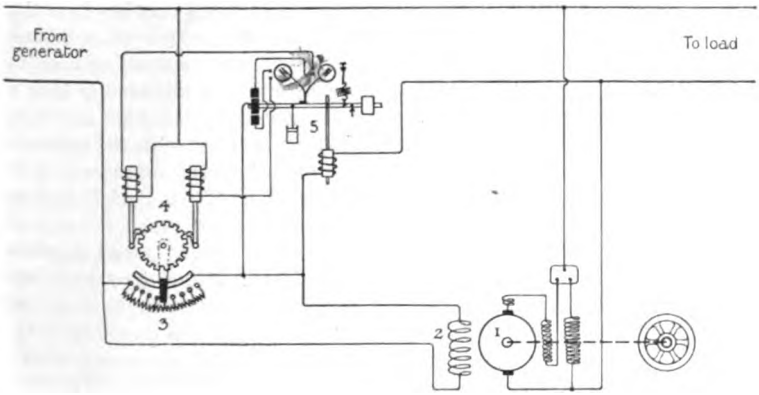

FIG. 1.—Lancashire Dynamo and Motor Company's Equaliser System.

1. Flywheel machine.
2. Special series winding.
3. Shunt resistance for B.
4. Solenoid operated regulator.
5. Automatic controller for 4.

machine coupled to a flywheel, the electrical machine being arranged to act as a motor and speed up the flywheel when the load on the system is below a certain value, and to act as a generator, slowing down the flywheel and returning power to the system when the load exceeds a certain value.* The operation of the machine is controlled by an automatic regulator, which in most systems operates to strengthen or weaken the field of the electrical machine.

It is evident that to obtain satisfactory equalising the electrical machine must be able to act either as generator or motor at any speed within the limit over which it is to work. Naturally the direct-current

* It will be noted that this definition does not cover the Ilgner and similar systems, for in the Ilgner system no energy is returned to the mains, as the flywheel equalises only for the particular load supplied by its own generator, and not for loads on other parts of the system. Thus the Ilgner set is not a load equaliser in the same sense as is a storage battery.

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machine suggests itself as being most suitable for this work, since by a variation of its field strength it can be made to act either as generator or motor over a wide range of speed; in fact, so well suited is the direct-current machine for this purpose that it is used not only on direct-current systems but also on alternating-current systems, the alternating current being converted to direct current simply to permit the use of a direct-current machine.

Equalisers for Direct-current Circuits.

One of the simplest forms of load equaliser for direct-current circuits is that made by the Lancashire Dynamo and Motor Company (Kelsall and Warburton patents), one of which was exhibited at the Manchester Electrical Exhibition, and was described very briefly in Mr. Wood's paper on this general subject, read before the Institution at Manchester two years ago. It consists of a direct-current machine coupled to a flywheel, and an automatic regulator which is adjusted to keep a constant output on the mains. The direct-current machine has three field windings—a shunt winding, a winding in series with the armature for overcoming the armature drop, and a special winding in series with the circuit on which the load is to be equalised. This special winding, which assists the shunt winding, is shunted by a resistance, the amount of which is controlled by the regulator. The system is shown diagrammatically in Fig. 1, its action being as follows: When the load on the mains falls below the average the decreased current through the special winding tends to cause the machine to motor and speed up the flywheel, thus taking power from the mains. As the flywheel increases in speed and the current falls, the regulator begins to cut out the resistance in shunt to the special winding step by step until the speed limit is reached. When the load exceeds the average value the process is reversed, and the regulator cuts in resistance at such a rate as to maintain a constant load on the circuit. A photograph of a flywheel set is shown in Fig. 2.

An interesting feature in connection with these sets is that the flywheels are run at a peripheral speed as high as 25,000 ft. per minute. A maximum speed variation of about 30 per cent. is usually allowed, thus permitting approximately 50 per cent. of the energy of the flywheel to be utilised.

Since the machine must work as either motor or generator over a speed range of 30 per cent., the commutating conditions are very severe, and commutating poles or other devices must be used to secure satisfactory commutation. The size of the machine is also considerably larger than that of an ordinary machine of the same rating and the same maximum speed, since it must be able to deliver full voltage at 30 per cent. below the maximum speed. The efficiency of this system, *i.e.*, $\frac{\text{power returned to mains}}{\text{power taken from mains}}$, should be well over 80 per cent.

The Lahmeyer Company patented in 1902 a load-equalising system which appears to resemble one of those mentioned in Mr. Wood's

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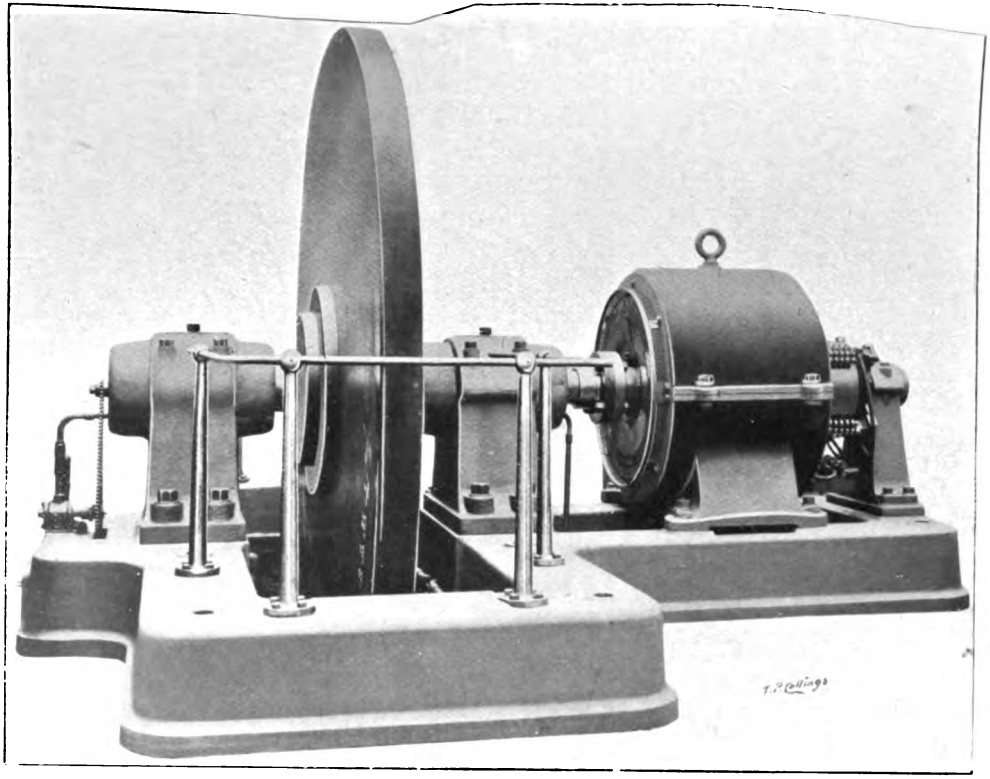

FIG. 2.—Lancashire Dynamo and Motor Company's Flywheel Equaliser for Direct-current Circuits.

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paper referred to above. This system is shown diagrammatically in Fig. 3. There are two direct-current machines, 1 and 2, coupled together and to a flywheel. The large machine, 1, works with a constant field, the small one, 2, with a variable field. The two are connected in series across the mains, so that the voltage of 2 is added to or subtracted from that of 1 according to the direction of the voltage on 2. When the voltage of 2 is at its maximum and opposed to that of 1, the voltage across the latter is a maximum and equal to that of the line plus that of 2. Under this condition the flywheel is running at maximum speed. If now a load above the average comes on the circuit, the voltage of 2 is decreased by means of an automatic regulator, which inserts resistance into the shunt field winding of 2, and the voltage across 1 is thus reduced. 1 therefore begins to generate, supplying power to the mains. In order that it may

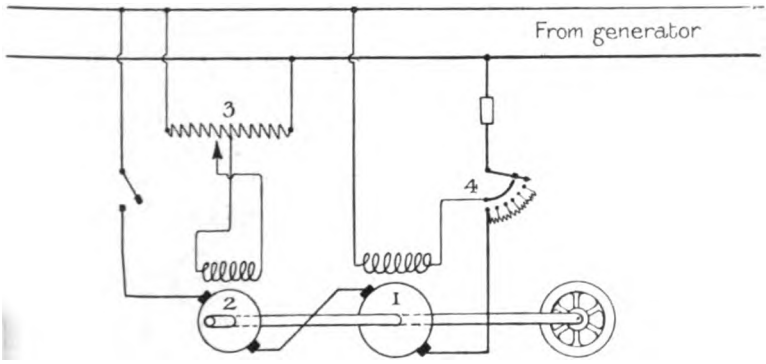

FIG. 3.—Lahmeyer System of Load Equalising for Direct-current Systems

1. Main equalising machine.
2. Auxiliary variable voltage machine.
3. Regulator for varying voltage of 1.
4. Starting rheostat for 1.

continue to generate as the speed of the flywheel falls, the voltage of 2 must be gradually reduced to zero and then increased to a maximum in the opposite direction. When this condition has been attained, the flywheel will have reached the minimum speed at which generation can take place. When the load on the system falls below the average, a reverse process with reference to the voltage of 2 is carried out, the flywheel is speeded up, and power is taken from the mains.

Since the machine 1 operates with a constant field, its voltage will vary directly with its speed, and if it is desired to regenerate over a speed range of, say, 30 per cent., it is evident that machine 2 must be able to give a voltage range of slightly over 30 per cent.—*i.e.*, it must be able to add or subtract about 15 per cent. of the voltage of 1. Thus 2 must have 15 per cent. of the capacity of 1, and since the two assist

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each other at low speeds, the regenerating capacity of the set is the sum of the capacities of the two machines.

One advantage of the Lahmeyer arrangement over that of the Lancashire Dynamo and Motor Company's is that with the latter a very heavy field winding is required in order to enable the machine to regenerate at low speeds, while with the former a heavy field winding

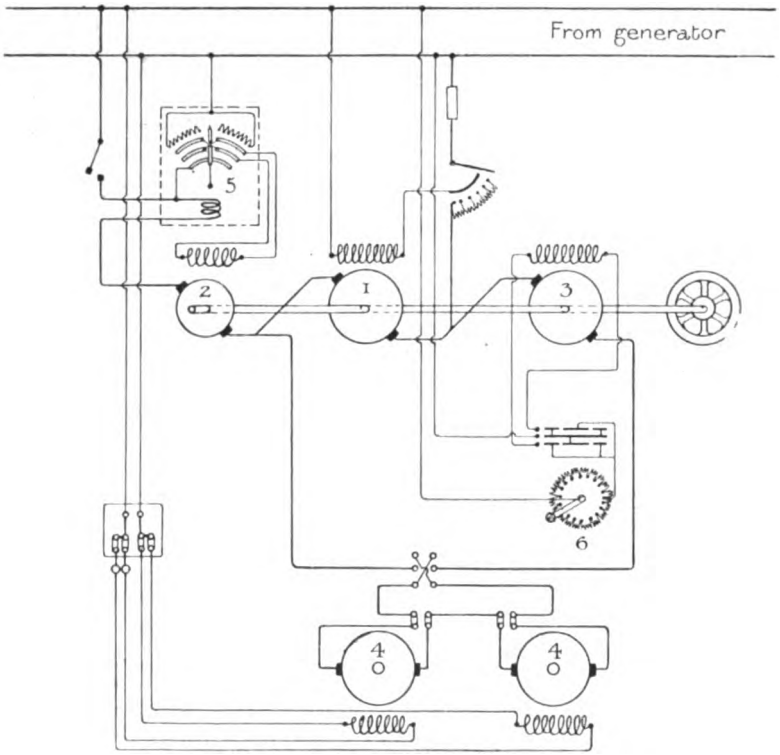

FIG. 4.—Lahmeyer Winding Engine with Load Equaliser, Direct-current System.

1. Main equalising machine.
2. Auxiliary variable voltage machine.
3. Machine for controlling voltage on winding motors.
4, 4. Winding motors.
5. Automatic regulator.
6. Controller for winding motors.

is required only on the small machine. The commutating conditions are very severe on the small machine, however, and it is probable that even on the large one commutating poles will be required. The regulator for the Lahmeyer system would probably be somewhat simpler than that for the Lancashire Dynamo and Motor Company's, since with the latter very heavy currents will have to be handled on

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equalisers of large capacity. On the other hand, the Lancashire Dynamo and Motor Company's system requires but one machine, while the other requires two. It would probably, therefore, have a somewhat better efficiency and lower cost, and would appear to be a somewhat simpler arrangement.

The Lahmeyer Company has installed a small electrical winding plant with load equaliser at Mines de Houille de Ligny-les-Aire. The arrangement of the system is shown in Fig. 4. The equaliser is similar to that described above. Two winding motors are used and connected in series. The voltage on these motors is controlled by means of a variable-voltage machine 3, connected in series with the main machine 1, and arranged so that its voltage is added to or subtracted from that of 1. To start the motors the voltage of 3 is brought to its maximum value equal to that of 1, and in opposition to it. There is then zero voltage on the motors. The voltage of 3 is gradually reduced to zero, and then brought up to a maximum in the opposite direction, when the voltage on the motors is a maximum, and equal to twice that of 1.

Still another type of direct-current load equaliser is that used by the British Westinghouse Company in connection with their rotary converter equaliser, which is described elsewhere in this paper. Other types have been devised, but those described above are sufficient to show the general principles upon which most of them work.

Equalisers for Alternating-current Systems.

There are two general classes of alternating-current load equalisers :—

(*a*) Those in which a rotary converter or synchronous motor-generator set is installed for changing from alternating current to direct current, and a direct-current machine with flywheel for receiving or delivering power through the converter or motor-generator.

(*b*) Those where an alternating-current machine is direct coupled to a flywheel, and the machine so arranged that it can act as motor or generator at any speed within the desired range.

Class A.—The best known equaliser in this class is the Westinghouse converter equaliser, which was first suggested by Mr. Rudolf Braun. A 500-H.P. equaliser has been in very successful operation for several months at the maritime pit of the Great Western Colliery Company in South Wales. The arrangement is shown diagrammatically in Fig. 5. 1 is the rotary converter; 2 the 3-phase transformer supplying it; 3 the direct-current machine; 4 the flywheel; and 5 the automatic regulator. The method of operation will be clear from the diagram. When the load on the mains is light, the field of 3 is

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weakened, and the flywheel speeds up. When the load is heavy, the field of 3 is strengthened, and energy is returned to the line through 1.

The rotary is provided with a series as well as a shunt winding. The two act in opposite directions when energy is being stored in the flywheel, and in the same direction when energy is being delivered by

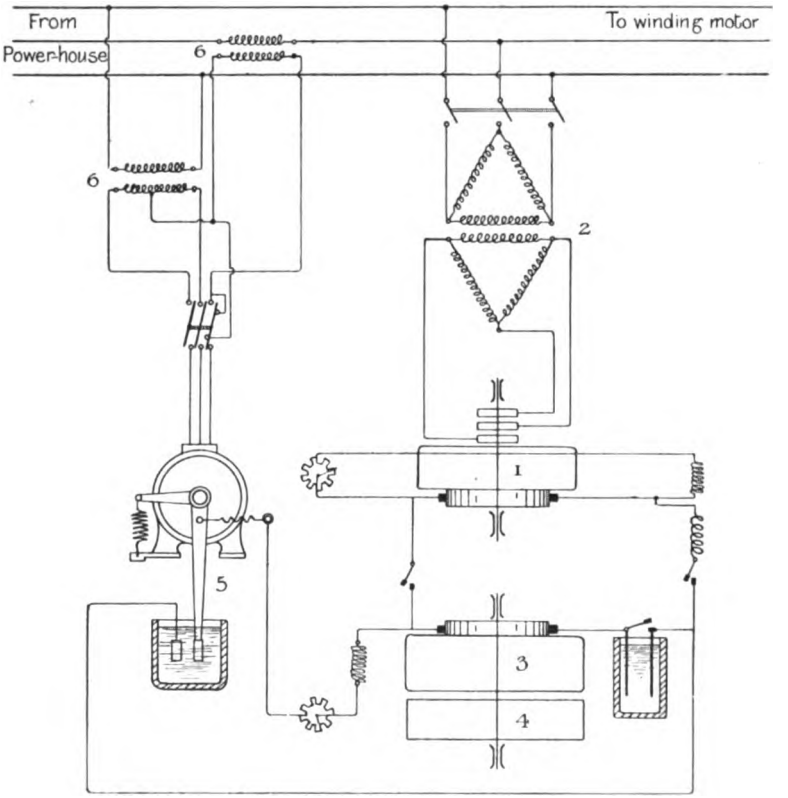

FIG. 5.—British Westinghouse Rotary Converter Equaliser System.

1. Rotary converter.
2. Transformers for supplying rotary.
3. Flywheel machine.
4. Flywheel.
5. Automatic regulator.
6, 6. Series and shunt transformers for controlling 5.

the flywheel. By making the shunt field rather strong, the rotary will work at approximately unity power factor when it is delivering direct-current power, and with a leading power factor when delivering alternating-current power. Thus it tends to compensate for the wattless current taken by the load. It can be used if desired without a series winding.

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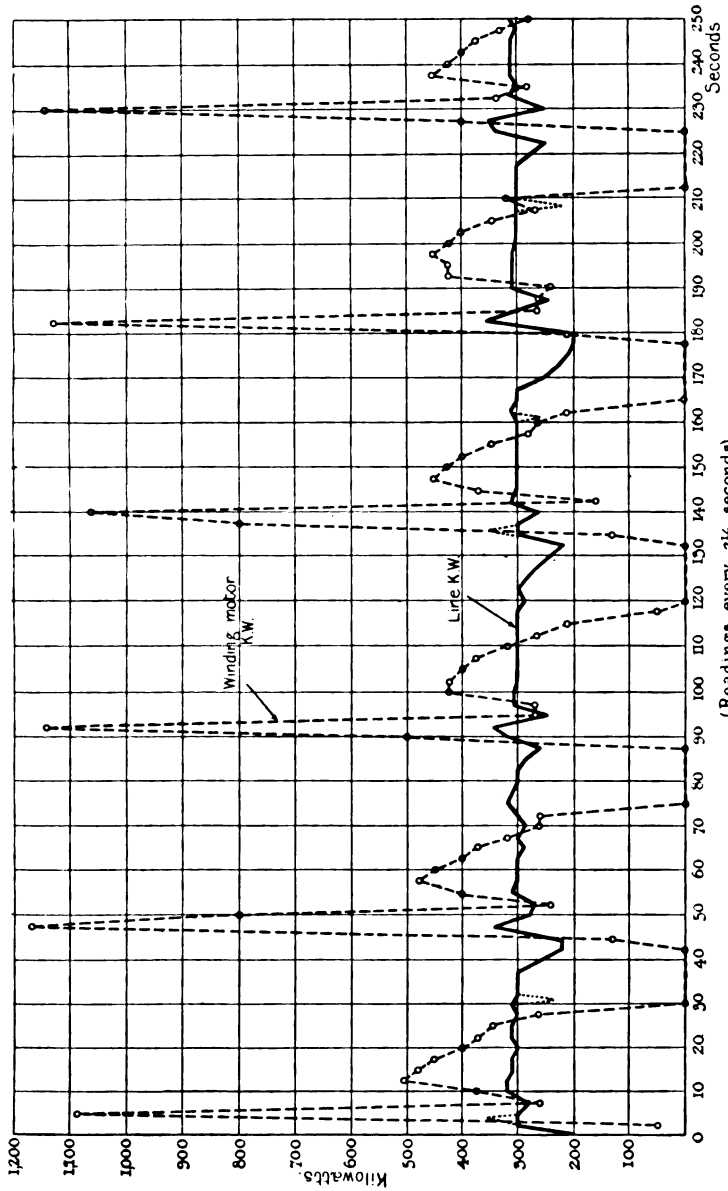

(Readings every 2½ seconds)

FIG. 6.—Great Western Winder.

(Tests of January 20, 1909.)

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A series winding was also placed on the flywheel machine, and connected in opposition to the shunt winding at discharge, the object sought being to prevent violent fluctuations in the charge or discharge rate due to sudden movements in the regulator, but as the regulator was provided with a rather stiff dash-pot, it was found that the best results were obtained by cutting out the series winding and working with the shunt winding only.

The field resistance is of the liquid type, and arranged to give a very wide range with a small movement. The resistance is controlled by a 3-phase induction motor, which is supplied from transformers in the main feeder. Originally the motor was supplied from three series transformers, but during the shop tests it was found that under certain conditions the equaliser would return energy to the power house and drive the main generators as motors, thus causing serious disturbances on the whole system. This is what might be expected from the use of series transformers, for the return of energy to the power house would mean a reversal in all three series transformers, and consequently no reversal in the direction of torque on the motor. The effect is evidently accumulative, for the greater the current through the transformers the greater the torque on the motor, the stronger the field in the flywheel machine, and the greater the rate of regeneration. To overcome this difficulty, two transformers were used, and connected as shown. This gives what is equivalent to a "watt" connection on the motor, and the regulator tends to maintain a constant kilowatt output on the mains. It is evident that a reversal in energy will cause a reversal in the direction of torque on the motor and so prevent the equaliser from supplying energy to the generating station. After this change was made in the transformers, no further trouble of this nature was experienced.

Very excellent equalising results are obtained, as will be seen from the curves in Fig. 6, which were taken during the official tests on the complete plant. The equaliser is set to maintain a load of 300 k.w. on the line, while the average for the time during which the readings were taken was about 294 k.w., which accounts for the reduced load taken by the equaliser set toward the end of each decking period. The peak loads on the motor are over 1,100 k.w., while the maximum output from the line is about 350 k.w. The necessity for an equaliser is apparent from the curves.

Fig. 7 shows the relation between time and revs. per minute of the winding motor. The guarantees made by the manufacturers for equalising and power consumption were shown by the tests to have been fully realised.

The Lahmeyer or the Lancashire Dynamo and Motor Company's system, with properly modified regulator, could be used as the direct-current flywheel set for this system. Below are given some data regarding the Great Western load equaliser and winding motor :—

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Winding Motor.—3-phase, slip-ring induction type, 2,200 volts, 25 periods, 700 H.P. Efficiency 91 per cent.

Transformer for supplying Rotary Converter.—3-phase, oil insulated, self-cooling, 450 k.v.a., 2,200 to 380 volts. Efficiency 97·8 per cent.

Rotary Converter.—6-phase, 400 k.w., 550 volts, 500 revs. per minute. Efficiency 94 per cent. Power required from mains to run rotary light, 15 k.w.

Flywheel Generator.—350 k.w., 550 volts, 750/500 revs. per minute. Efficiency 93·5 per cent. The generator has cast-iron yoke with laminated poles, commutating poles, and compensating winding. Power required from mains to run rotary and flywheel generator at maximum speed, 35 k.w.

Flywheel.—Weight 22,000 lbs., diameter 6 ft. 1 in., width 3 ft. 6 in.

Stored energy at 750 revs. per minute, 24,000 H.P.-seconds.

Stored energy at 500 revs. per minute, 10,700 H.P.-seconds.

Stored energy available, 13,300 H.P.-seconds = 440 H.P. for ½ minute.

Overload capacity of all apparatus, 100 per cent. for short periods.

Efficiency of load equaliser, *i.e.* $\frac{\text{power delivered}}{\text{power received}} = 74$ per cent.

It is often desirable to operate a rolling mill or winding engine by means of a very slow-speed induction motor from a 40- or 50-period circuit. If a speed of 60 revs. per minute is required the motor must have approximately 100 poles on a 50-period circuit and 80 poles on a 40-period circuit. The cost of a motor with such a number of poles is very high, while its efficiency is poor and its power factor so low as to almost preclude its use. To overcome this difficulty, and at the same time to provide a load equaliser, the author has devised the arrangement shown in Fig. 8. This scheme is somewhat similar to the converter equaliser of Braun, except that the rotary is replaced by a motor converter, and the winding or mill motor supplied from the connections between the rotor and the direct-current armature of the motor converter. The direct-current flywheel machine and the regulator are the same as are used with the converter equaliser set. The equalising action will be readily understood. When the load on motor 1 is below the average the machine 4 acts as a motor and speeds up the flywheel. When the load on 1 is heavy 4 becomes a generator, and supplies alternating current to 1 through machine 3. At the same time 2 also supplies alternating current to 1, so that the power for driving 1 comes partly from the flywheel and partly from the line. Thus motor 2 need be large enough to supply only the average load of the motor 1, the peaks being taken care of by the flywheel through 4 and 3. 4 may be compound wound, or it may be run with a very stiff field in order to compensate for the magnetising current taken by the motor 1. The great advantage of this system is

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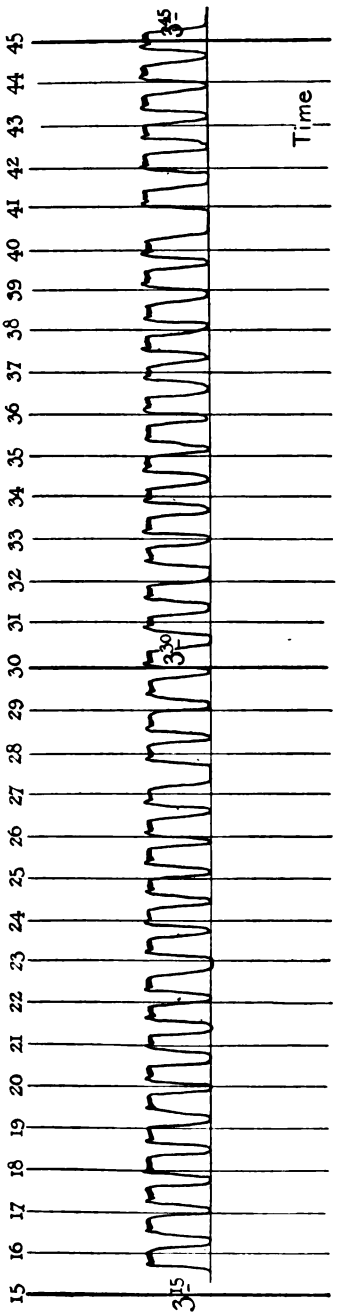

FIG. 7.—Great Western Winder: Winding Motor—Speed Curves.
(Tests of January 20, 1909.)

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that it permits motor 1 to be operated at a frequency much lower than that of the line. For example, if 2 and 3 have the same number of poles, the frequency on 1 will be one-half that of the line. If 2 has 10 poles and 3, 6 poles, the frequency on 1 equals line frequency by $\frac{6}{16}$—*i.e.*, if line frequency is 50, that on 1 is 18¾. Thus for 60 revs. per minute the motor would have 36 poles instead of 100, as would be required if operated directly from the line. This means a great

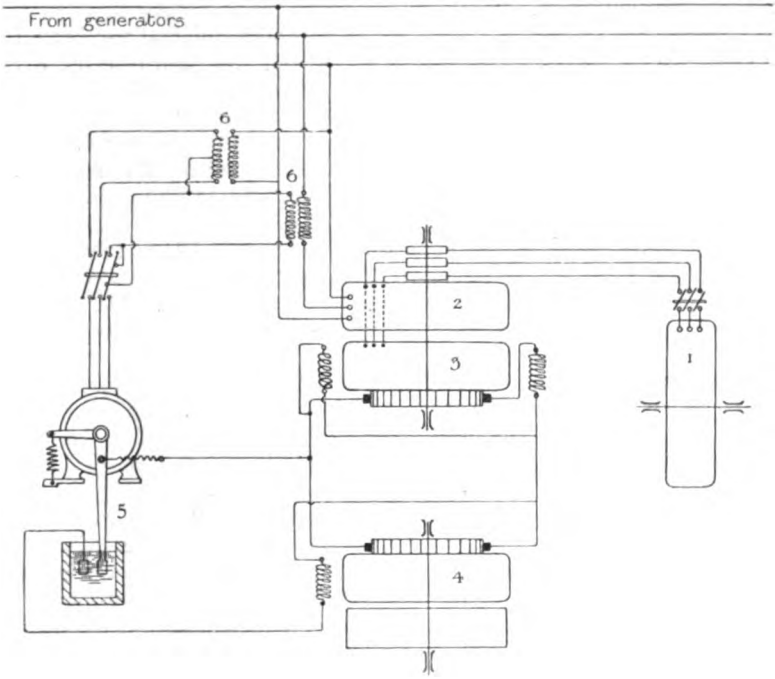

FIG. 8.—Motor Converter Equaliser for Slow-speed Motor and High-frequency Circuits.

1. Winding motor.
2 and 3. Motor Converter.
4. Flywheel machine.
5. Automatic regulator.
6, 6. Transformers for supplying 5.

saving in the cost of the motor, with a corresponding improvement in power factor and efficiency.

One objection to this system is that the motor cannot be operated if the motor converter is disabled, though it could be operated at a reduced output without the flywheel machine.

The motor 1 may be 3-phase or 6-phase, and by putting the slip-rings between 2 and its outboard bearing, the rotors of 2 and 3 may be placed as near together as desired and the middle bearing omitted.

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With the regulating transformers placed in the position shown, equalisation of load is obtained only in so far as motor 1, or other motors on the same circuit, are concerned, but by putting the regulator transformers in the main circuit the equaliser will within its capacity maintain constant load on this circuit.

Class B.—In his paper referred to above Mr. Wood described two equalising systems in which alternating-current machines were coupled direct to the flywheel, so that no conversion from alternating to direct current was required.

In the first system two induction motors with different numbers of poles are coupled together and to a flywheel. To speed up the flywheel one motor is used and the other cut out, so that the flywheel reaches a speed almost equal to the alternations per minute of the supply circuit divided by the number of poles of one motor. For returning power to the mains the motors are connected in cascade. In this case the synchronous speed is equal to the alternations per minute divided by the sum of the poles of the two motors. They are, therefore, operating above synchronous speed, and will act as generators, the amount of current delivered being controlled by varying the resistance in the secondary circuit of the second motor. The objections to this system are the large magnetising currents and the heavy rheostatic losses in the controller.

In the second system the rotor of an induction motor is coupled to a flywheel, and both primary and secondary are arranged to rotate. When primary and secondary rotate in the same direction the flywheel reaches a speed greater than the normal synchronous speed of the motor. If, then, the primary is slowed down and gradually brought up to speed in the opposite direction, the motor will be running above synchronism and will deliver power. The speed of the primary is controlled by an auxiliary motor. The power factor of this system is much better than with the other, but the mechanical difficulties appear so serious as to make the system impracticable, at least for large sizes. The method of controlling by means of auxiliary motors is also rather complicated.

The author has devised a system which he believes possesses a number of advantages over any system heretofore proposed for alternating-current equalisers. Its use is limited, however, to systems of low frequency—*i.e.*, 25 periods or lower. It consists simply of one or more single-phase commutator type machines, similar in general design to a single-phase compensated series railway motor. The motors are direct coupled to a flywheel, and arranged so that they can act as motors or as generators at any speed within the desired limits.

It is well known that a single-phase series machine may be run as a generator, and if the field is excited by alternating current an alternating current of the same frequency will be generated by the armature, but as the field is highly inductive and as the voltage on the armature is in phase with the fluid flux, this voltage

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will be almost at right angles to the voltage impressed on the field. Consequently the field of the machine should be supplied with a voltage approximately at right angles to that of the circuit to which its armature is connected, and means must be adopted for obtaining voltages of the proper phase. If this is done the speed of the machine may be changed, and it may be made to act as motor or generator at any desired speed by a simple adjustment of the voltage across the field. Fig. 9 shows one way in which the system may be operated on a 2-phase circuit. Two single-phase machines, 1 and 2, are coupled together and to a flywheel. The armature of 1 is supplied from

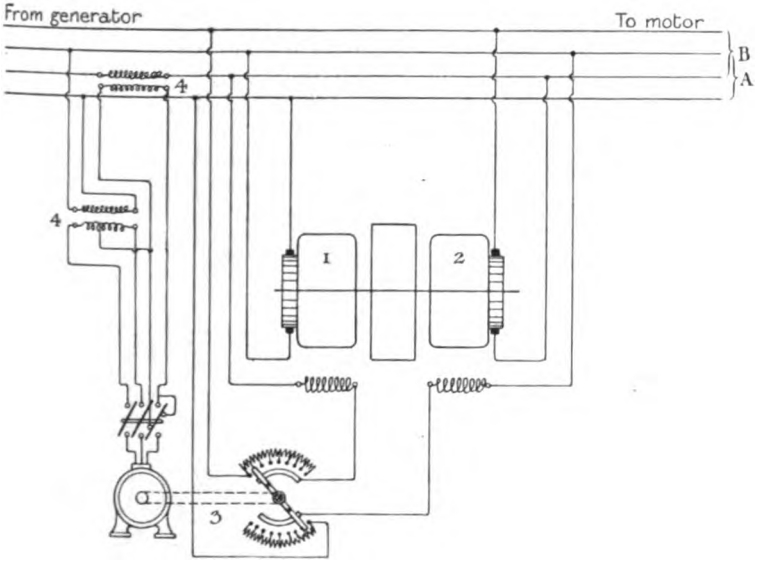

FIG. 9.—Load Equalising by means of Single-phase Commutator Type Machines.

1 and 2. Single-phase flywheel machines.
3. Automatic regulator.
4. 4. Transformers for supplying 3.

phase A and its field from phase B. Similarly the armature of 2 is supplied from phase B and its field from phase A. Thus the desired phase relations between field and armature are secured. The field voltages are controlled by means of the automatic regulator 3, which cuts resistance in or out of the circuits. This resistance preferably should be inductive, in order that the phase relations between current and voltage may not be disturbed in the field circuit.

Instead of using field control as described above, the same result might be secured by means of armature control. In this case a transformer with a number of tappings would be placed between armature and line. By changing from one tapping to another, the voltage ratio

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between armature and line would be changed, and the machines changed from generators to motors as desired. A combination of field and armature control could, of course, be used.

The current for magnetising the fields of a single-phase machine is considerable, and as it is practically wattless, it has an effect upon the power factor of the line. This objection is overcome by exciting the field from an alternator driven by a synchronous motor. This arrangement

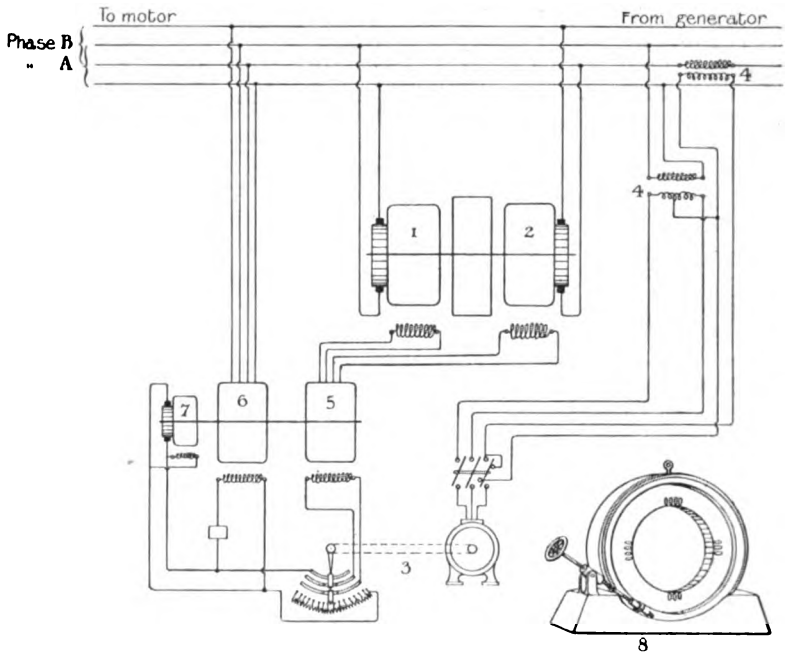

FIG. 10.—Load Equaliser for Alternating-current Circuits.

1 and 2. Single-phase machines.
3. Automatic regulator.
4. Series and shunt transformers for supplying 3.
5. Alternate-current exciter.
6. Synchronous motor.
7. Direct-current exciter.
8. Device for adjusting phase angle of 6.

is shown in Fig. 10, where 5 represents the exciting alternator, 6 the synchronous motor, and 7 a small direct-current machine for exciting the fields of the synchronous machines. It is evident that by varying the field strength of 5, the fields of the single-phase machines may be controlled as desired. The voltage regulator with this system will be small and easily operated. Motor 6 may be very small, since the current delivered by the alternating exciter is practically all wattless. 8 shows an arrangement for shifting the stator of 6 circumferentially with reference to the stator of 5, in order that the phase of the voltage

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of 5 may be shifted with reference to that of the line, thus permitting the single-phase machines to deliver leading currents to the line to compensate for lagging currents taken by other apparatus.

To reduce the size of the exciter sets, the arrangement shown in Fig. 11 may be adopted. Here the alternating exciter is connected in series with the line, and arranged so that its voltage may be added to or subtracted from that of the line. If a speed variation of 30 per cent. is required, the exciter need have only about 15 per cent. of

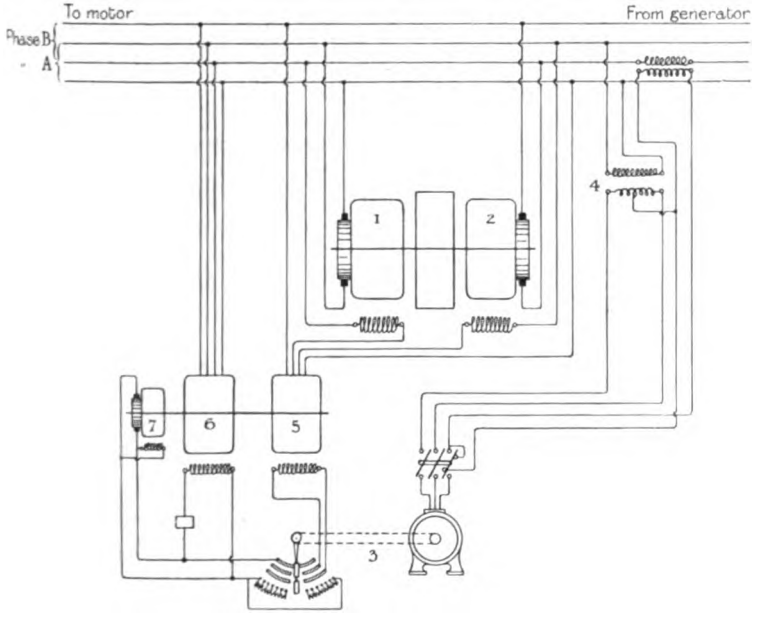

FIG. 11.—Load Equaliser for Alternating-current Circuits.

1 and 2. Single-phase machines.
3. Automatic regulator.
4. Series and shunt transformers for supplying 4.
5. Alternating-current exciter.
6. Synchronous motor.
7. Direct-current exciter.

the capacity of the exciter shown in Fig. 10, so that the capacity of the whole exciter set would be very small.

For 3-phase circuits two transformers may be used with Scott connection for changing from 3-phase to 2-phase, and two motors employed, or three motors may be used, one supplied from each phase. The fields may be excited by a 3-phase alternator, or from the line through transformers connected to give the proper phase relation between field and armature. Fig. 12 shows a 3-phase equaliser and one method of securing field voltages at right angles to armature voltages.

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Possibilities for the Use of Flywheel Load Equalisers.

When considering the advisability of installing a flywheel load equaliser, the following points will probably prove the determining factors :—

1. Nature of load.
2. Capacity of generating station.
3. Regulation of system.
4. Distance of load from generating station.

Nature of Load.—As was fully explained in the first part of the paper, the flywheel equaliser is suitable only when the peak loads are high and of short duration.

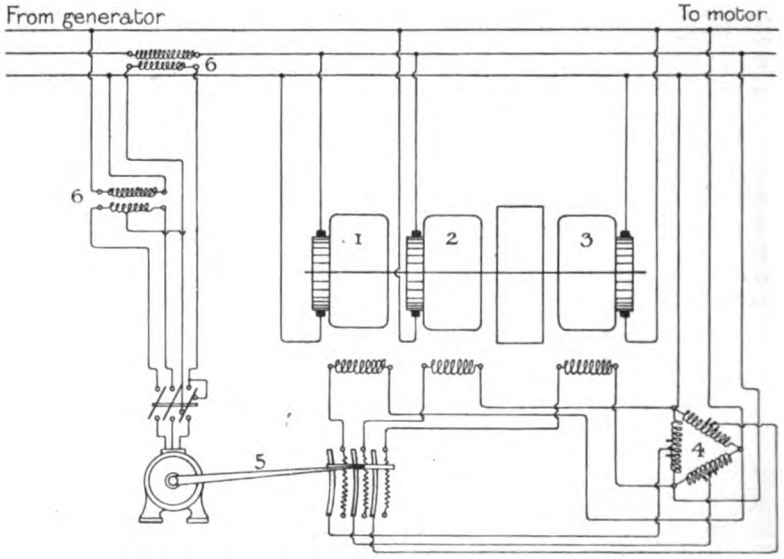

Fig. 12.—Load Equaliser for 3-phase Circuits.

1, 2, 3. Single-phase motors.
4. Transformer for supplying current to field windings.
5. Automatic regulator.
6, 6. Series and shunt transformers for controlling regulator.

Capacity of Generating Station.—When the generating station has ample capacity for dealing with heavy peak loads, the use of a flywheel equaliser need not be considered, in so far as peak load reduction is concerned, but where the station cannot stand the peak loads, an equaliser may prove much cheaper than additional generating plant. It may happen that a generating plant has ample capacity for standing the peak loads thrown on it by a large motor when the motor is first installed, but as the station load increases the plant may become overloaded, and a flywheel equaliser be very desirable.

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Regulation of System.—Although the generating station has ample capacity for supplying the peak loads, the effect of these loads upon the regulation of the system may be so bad as to make a flywheel equaliser very desirable.

Where a generating station supplies a large number of different classes of work, it is not likely that the nature of the load will be such as to make the use of a flywheel equaliser advisable for smoothing out the load on the whole station, though one may very likely be used to advantage to equalise the load taken by a single customer. Its greatest field, however, will be for equalising the load on a single motor or group of motors used for the same class of work.

It is the author's opinion that the direct-current flywheel equaliser is not likely to come into very extensive use, as the majority of large systems generate alternating current, and it appears to be the practice now to instal alternating-current motors wherever possible, instead of converting to direct current. Also the question of regulation is not so serious on direct as on alternating-current circuits.

Most of the large supply companies and corporations situated in the coal or steel districts expect the collieries and steel mills to become their largest customers, but a large part of this load is likely to be used for rolling mills and electric winding, a demand which on account of its intermittent nature is much more desirable if the peaks and hollows of the load be smoothed out. When the motors are of large size, or the capacity of the station almost reached, or when violent fluctuations in the load affect seriously the regulation of the whole system, a flywheel load equaliser is desirable, if not essential.

Discussion.

Mr. Miles Walker : The problem of equalising the load is difficult, because so many things require to be done at the same time. First we have a machine which is to be started, then we have another machine which is to take a very heavy peak, then probably our source of supply is from an alternating-current system at high frequency, so that all the requirements of the plant are difficult to meet, and all the means for supplying it are of the opposite kind to what is wanted. It is interesting to note that in many of the methods advocated a commutating machine is made use of, both for getting a good starting torque and also for operating upon the flywheel, whose speed must be changed and which must both receive and give out power, for either of which purposes the commutating machine seems very well adapted. You will notice, however, from the last paragraph in the paper that notwithstanding the fact that the commutating machine has the right characteristics, the tendency is to do away with it, and to use an induction motor. It is quite possible to use an induction motor for starting if we are prepared to waste a certain amount of power in the rheostat, and in some cases this plan is preferred rather than the employment of a commutating machine. It would seem that if we could in

Mr. Walker.

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Mr. Walker.

some way still use the alternating-current motor and do away with the loss from the rheostat, we should have a much more satisfactory apparatus. If we are going to have a commutator at all on an alternating-current system, it would almost be better to use a system like some of those already mentioned, in which the commutator instead of dealing with the whole voltage of the motor deals with the motor circuit at a low voltage. It is possible to change the speed of an induction motor through a wide range by changing the voltage of the rotor by means of an exciter having a commutator, and although the exciter has to deal with the whole current, it does not have to deal with the whole voltage, and this would seem to be an advantage. If you take the system put forward by Mr. Wood on page 186, and connect a polyphase exciter to the induction motor, so as to be able to change its speed independently of the load on the motor, I think we should have a fairly efficient load equaliser, and one which would work at high frequencies just as well as at low frequencies. Then again, if we use the induction motor for such work as driving rolling mills with varying loads, we might use the exciter for changing the speed at once to take energy out of the flywheel without using a rheostat.

Mr. Wilson.

Mr. H. W. WILSON: I have had a considerable amount of experience with the use of buffer batteries on variable load systems, an arrangement which has been on the whole satisfactory as regards equalisation of load. The great drawback to it is the heavy depreciation of the battery. My firm recently installed a flywheel load equaliser in a plant where a battery and a reversible booster had been in use for about three years. At the end of this period the battery was practically destroyed, and so far as the running results up to the present time are concerned, we find that a flywheel load equaliser produces the same effect as the battery, and does it much more satisfactorily. In this particular case the working voltage is about 550, the peak load about 220 amperes, the average running load 80 amperes, and for half the time the load drops down to about 12 amperes. The peak comes on very suddenly, and without a battery or a load equaliser of this type a very severe strain would be thrown on the generating plant, which is gas-driven, and would cause grave concern for the life of the gas engines. What I have seen of the plant shows that the load equaliser takes roughly about 40 to 50 per cent. of the peak load comfortably, and gets the plant over the maximum load, which lasts less than a minute. After that the engine is able to run satisfactorily, and, when the load has fallen away, the energy is restored to the flywheel system, and the speed is again increased. The cost of an equipment such as the author mentions is much less than the cost of a battery and reversible booster, and the depreciation is also very much less, so that there can be little doubt that for a load such as I have described, a load equaliser of this kind is the most satisfactory. Of course, where the peaks are of a longer duration, it is difficult to get sufficient energy into the flywheel to carry you over. Unfortunately there is very little information available in this country of actual running results from plant of this

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kind over lengthy periods, and it is not easy to say how it actually compares in efficiency with a battery, when the latter is kept in good condition. The battery in the case I have referred to was not in good condition, and its efficiency was probably not more than 30 per cent., and there is no doubt that the efficiency of the flywheel load equaliser is very much higher. But prejudice dies hard in this country, and my experience has been that people who have had a battery seem to become greatly attached to it whether it is good or the reverse, and they express great fear that if a flywheel equaliser were driven at too high a speed it might burst and cause a serious accident. Mr. Wilson.

A case came to my knowledge some years ago in which a small tramway company was being supplied with power at a considerable distance by a generating station, which was selling the current to them, and in that case they had a reversible traction booster, and a small battery in a sub-station of their own some 2½ miles from the generating station. The advantage of this arrangement was a great saving of money on the cables, and in that way I think an apparatus of this kind would be very useful if it could be put in close to the motor load, either on the consumers' premises or in a sub-station in the district, or in small traction systems where the peaks are very considerable, and altogether out of proportion to the average load. As far as my experience goes, it is difficult with a plant of this kind located in the generating station to get anything like as good a voltage regulation as you can with a battery. In the first case I mentioned the generators themselves are not particularly good in regulation, and it is more difficult to make the voltage hold up with the flywheel load equaliser than with the battery, although the battery was in very bad condition and had a very low efficiency. I have had no experience of flywheel systems on alternating-current machinery, nor do I know of the actual working results of such a system having been published.

Mr. V. A. H. McCowen: As far as the application of a load equaliser to a public supply system is concerned, it would appear to me that the generating station is hardly the place to instal it. In a public supply, owing to the many different purposes for which current is used, the load flattens out at the station, and I think probably the best place to fix an equaliser would be in the remoter districts, where one gets abnormal peaks, and thus keep the feeders evenly loaded. The same thing occurs with large tramway loads; you get a flattening of the peaks, which renders a machine of this kind comparatively useless, but in small tramway loads I believe it would have the effect of reducing the amount of power necessary to meet the demand. Mr. McCowen.

Mr. C. F. Smith: It is interesting to notice the similarity in the auxiliary machinery employed in connection with the two types of load equalisers—the flywheel and the storage battery. The arrangement of series boosters, differentially wound motors, etc., shown in the early part of the paper, bears a remarkable similarity Mr. Smith.

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Mr. Smith. to the corresponding diagrams for a battery booster regulating installation. Mr. Peck has discovered a use for a much-neglected machine, viz., the shunt alternating-current motor. The series single-phase motor is often employed, but the shunt motor has so far been looked upon as useless. The difficulty with a shunt alternating-current motor is that the current in the field circuit lags very much behind the terminal voltage, and when the power factor of the armature circuit is high, there is a large difference of phase between the field and the armature current, and consequently a low torque. Now, if there be only a small current in the shunt circuit, and possibly a resistance to bring the power factor up to a comparatively high value, the motor will have a very good torque over quite a considerable range of speeds. A close approximation to coincidence in phase between the current in the field and the armature can be obtained throughout this range, and therefore a satisfactory torque and fairly good power factor. The shunt machine, when used as a generator, has many advantages. It has a constant frequency, independent of speed, and by compensating for armature reactions, I imagine one could get terminal voltage which would be almost independent of the power factor of the load circuit. It is interesting to me to see the shunt motor come into practical use, although I notice that it is referred to in the paper as a series motor. I think the shunt motor ought to get the credit where it can. I should like to suggest that by using a shunt-winding of many turns, and taking only a small current, it might be possible to dispense with the special exciter, especially on a 3-phase circuit, where a choice of phases for the supply is available for giving the desired phase relation.

Mr. Thomas. Mr. EUSTACE THOMAS: We have made the switchboards and automatic gear for one or two of the equalisers in use. My impression is that the switching and automatic arrangements will probably be simplified with advantage as time goes on, and it has occurred to me several times that perhaps in the future something may be done towards making the generating plant act as its own equaliser, by enabling its flywheels to work over a greater range of speed, and to supply some of the energy now supplied by a separate equaliser. I suppose most cases of flywheel equalisers at present are considered in relation to existing plants, but in the future it may be possible to consider the matter in reference to plant which is not actually put down. It does certainly seem that it would be possible to arrange a regulating system on the field of the machine which will give you a sufficiently uniform voltage, even though the speed of the generating plant may vary over quite a wide range. Of course the horse-power of the plant would go down with lower speed, but even with this there might possibly be some advantages with very violent peaks, such as occur with winding plant.

Mr. McKinnon. Mr. E. C. MCKINNON: In the paper the author gives the battery its proper place as a load equaliser, and I do not think Mr. Peck should have gone from that standpoint in his opening remarks, where he stated

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that a battery was not suited to sudden and rapid fluctuations of load. I submit that it is admirably suited to these conditions, provided it works in conjunction with a reversible booster, which must, of course, be instantaneous in its action; a differential booster would not suffice. The author states that the energy from a battery cannot be taken out rapidly in a few seconds, as in the case of the flywheel load equaliser, but the battery would yield its output just as rapidly up to the capabilities of the booster. I do not think Mr. Peck is correct in stating that a flywheel load equaliser is more efficient than a battery. He states that the efficiency of a flywheel equaliser is 0·74 per cent. (no doubt this is a slip for 74 per cent.), whereas a storage battery working on a rapidly fluctuating load will give an overall efficiency throughout a working day of at least 85 per cent. It is true that the efficiency of a battery on a long continuous discharge is about 75 per cent., but, working on a fluctuating load, and only giving out a relatively small proportion of its maximum output, it gives a very high efficiency, 85–90 per cent. Mr. McKinnon.

In discussing the advisability of installing a load equaliser, Mr. Peck apparently refers only to flywheel equalisers, but there are several important considerations beyond those stated, as regards the installation of load equalisers in general. For instance, some saving to the engineer might be claimed for the apparatus, and if so, I think engineers would be largely guided by the extent of the saving.

With reference to Mr. Wilson's remarks, more especially where he refers to the deterioration of the battery as being very rapid, I have good reason to believe that I know the installation he refers to, and can give a very good explanation why that particular battery deteriorated. It happens to be a case where the battery is fixed on a transporter bridge in a small town, where the gas supplied from the mains is of very inferior quality. The engineers inform me that when they have come in the morning to start up the gas engine, it has sometimes been nearly half an hour before they could get the machine to run, and meanwhile they have used the battery instead. If a battery is intended solely as a load equaliser, it naturally deteriorates when repeatedly used, in addition, as a main generator.

It is not correct to talk about the efficiency of a battery dropping to 30 per cent. This fact is very frequently confused, to the detriment of the battery. If an efficiency of only 30 per cent. is obtained, it signifies that the battery is receiving over 50 per cent. unnecessary charge. The real efficiency of a battery is found by putting back on charge the amount taken out on the previous discharge, plus an amount required to bring the cells up to a full state of charge, the difference representing the inefficiency of the battery. The efficiency of a battery is practically constant throughout its life. It is the capacity of the battery which may fall, but not its efficiency.

Mr. J. S. Peck (*in reply*): Mr. Wilson asked about working results. The only plant with which I have any acquaintance is that at the Great Western Colliery, in which the equalising results are very good, Mr. Peck.

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Mr Peck.

as will be seen in Fig. 6. The overall efficiency of the complete plant —*i.e.*, units from line per ton of coal raised—is within the guaranteed value. The plant has now been running for several months, and except for a few minor troubles which developed soon after it was started, the working has been entirely satisfactory. Mr. M'Cowen mentioned the desirability of placing the load equaliser near the load to be equalised. I quite agree with this, for if it were placed in the generating station it would not equalise the load on the feeders, which is one of the things desired. In my remarks on the last page of the paper, where I referred to equalisers placed in the generating station, I meant to convey the idea that this was an arrangement which would very seldom be feasible. It is possible that the flywheel load equaliser will be useful on small tramway systems, but this will depend almost entirely on the nature of the load.

Mr. Smith referred to the fact that I had called this a series machine when it was really a shunt machine. Of course it is a shunt machine, but in design and construction it is practically identical with a series compensated motor, except that it is operated as a shunt machine instead of a series machine.

Mr. Thomas asked whether flywheels could not be used on the generators. We had one case where a comparatively small alternating-current generator supplied a motor for driving a haulage plant, and we seriously considered the question of putting a heavy flywheel on the generator and arranging the governor of the engine so that when the normal load was exceeded the machine would slow down and permit the flywheel to help out the engine. This arrangement would be possible with alternating current only where there is no objection to fluctuations in frequency. If additional apparatus had been supplied from the same generator such a system would not have been feasible. With direct-current machines it would be possible to put on an automatic voltage regulator and permit the speed to drop, but this would require a large margin in the field, since a maximum voltage would be required when the speed is below normal. Regarding battery discharge rate, the idea I meant to convey was that a battery is not suitable where it must be fully charged and completely discharged in the course of a few seconds. I stated in my paper that it would be possible to put in a storage battery large enough to handle any load, but it would hardly pay to put in a battery where the load rises several hundred per cent. above normal in the course of a few seconds, and then drops to zero in a correspondingly short time. The efficiency that I gave for the Great Western plant should be 74 per cent., and not 0·74 per cent. It must be remembered, of course, that this is an alternating-current system, and if a battery is used on an alternating-current system, a rotary converter with transformers or a motor-generator set will be required.

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NOTES ON SAFETY OF WORKING ELECTRICAL PLANTS IN COAL-MINES.

By SIDNEY A. SIMON, B.A., Associate Member.

(*Received from the* GLASGOW LOCAL SECTION *February 6, and read at Glasgow on March 9, 1909.*)

Now that the new rules of the Home Office have been in force for some considerable period, and the fresh impetus thus given to the development of electricity in mining operations has had time to show some effects, it is interesting to cast a glance over the achievements and to discover what are the lessons to be learned from the experience gained.*

In the first place, and this is a noteworthy fact, and one upon which all connected with the electrical industry can congratulate themselves, there has been a remarkably small number of serious accidents involving loss of life or injury to persons or property. And particularly no accidents have occurred which have occasioned explosion of firedamp or coal dust—a danger so intimately connected with coal-mining to which one may safely say the framing of the rules was primarily due. In point of fact, so far as danger to persons and property is concerned, except in this one particular, electricity in mines does not differentiate itself materially from electricity in a large number of other branches of industry.

This would tend to show, on the one hand, that engineers and colliery owners are working along the right lines, and on the other, that the danger of electricity may have been exaggerated, so that with good work carried out by reliable people with a reputation at stake these dangers become fairly insignificant.

This should not, however, be taken as a reason for relaxation of precautions, for although the danger of an accident may not be imminent, yet the effect of one occurring might—and probably would—be very disastrous.

It is therefore desirable to find out what are the lessons to be learned from the experience gained during the last three or four years as a guide to future developments, especially with a view of obtaining the greatest economy in initial outlay compatible with safety.

The past immunity from accidents makes the problem much more difficult, as there is, in consequence, no indication by actual experience as to which of the variety of protective designs which have been utilised and which are put forward as the best or only means of securing perfect safety by their respective supporters, may be less safe and more likely

* This paper was written before the accident at the Featherstone Colliery on January 21, 1909.

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to cause a disaster than any one of the others. It is, however, absolutely necessary to determine the value of the claims put forward by those favouring any particular design of protective device, as the consequence of any error in this respect might have such disastrous effects of so far-reaching a character as seriously to interfere with the development of the electrical industry in its application to collieries.

On the one hand, such an investigation might lead to the necessity of adopting designs which in point of cost would prohibit the use of electricity entirely (from a commercial point of view), while on the other hand, it might show that costly designs for so-called protection are really sources of danger which defeat their own ends.

The special rules distinguish between two distinct classes of location of electrical apparatus, viz.: (1) Places or parts of mine where General Rule No. 8 of the Coal Mines Regulation Act, 1887, applies; (2) all other places. This rule is quoted verbatim below.*

Rule 37 (Section V., Motors) only provides for the enclosure of all current-carrying parts of motors, switches, starters, and accessories in flame-tight non-inflammable enclosures of sufficient strength to resist the effects of an explosion in the interior in all locations under Class 1, unless the place in question is a room separately ventilated with intake air.

It would, therefore, appear that according to these rules, in all locations under Class 2, as well as such locations under Class 1, which can be separately ventilated with intake air, no special protective devices are called for except such as would be dictated by common sense or ordinary engineering experience to comply with the local conditions obtaining in similar locations in any other branch of industry.

In underground working the atmosphere is usually warm and very often damp, whilst in many cases, such as in the neighbourhood of pumps, it may be charged with moisture, or there may even be water actually dripping from the roof or leaking pipes, splashed from projecting rocks, or sprayed from the pumps.

Due precautions should therefore be taken that the insulation of the winding and current-carrying parts is of a character to resist the continued action of moist atmosphere. The insulating material used

* Extract from the Coal Mines Regulation Act, 1887:—

"RULE VIII.

"*Use of Safety Lamps in Certain Places.*

No lamp or light other than locked safety lamp shall be allowed or used

"(*a*) In any place in a mine in which there is likely to be any such quantity of inflammable gas as to render the use of naked lights dangerous, or

"(*b*) In any working approaching near the place in which there is likely to be an accumulation of inflammable gas.

"And when it is necessary to work the coal in any part of a ventilating district with safety lamps, it shall not be allowable to work coal with naked lights in another part of the same ventilating district situated between the place where such lamps are being used and the return air way."

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for high-tension work is generally better suited to stand this action than that commonly used on low or medium pressures, and it is therefore specially important in cases where medium pressure is employed to pay particular attention to the class and method of insulation, and to avoid the use in it of any material of a hygroscopic nature.

The accumulation of coal dust on the windings should be avoided as much as possible, as it might form a conducting film or layer over the insulation to the frames. Periodical inspection and cleaning should be enforced as a preventative.

From the above considerations it will be clear that the motors should be placed in well-built chambers, properly lighted and ventilated with intake air, where there is less likelihood of water dripping from the roof, and where there is light for inspection and room to give access to all the working parts of the motor, and to which, by being as far as possible shut off from the main roadways, there is less liability for the penetration of coal dust. Such chambers can easily be kept clean, and the writer has seen many of them in Continental mines, which, with their arched roofs and spotless tiled pavements, it was difficult to conceive were 600 or 700 yards below the surface of the ground.

The engine-man having care of machinery in such a chamber has every inducement to take a pride in the condition of his charge, and is thus stimulated in his attention, with decided advantages to the owners.

Wherever possible, therefore, the location of electric machinery in such chambers should be resorted to, and then no special protective device would be required, but standard machines would meet all requirements.

If it is impossible to avoid dripping or spraying water by building the chamber with waterproof arches and walls, or by arranging a suitable roof over the motor to lead off the water and prevent it dropping on to the motor, it is necessary to have recourse to enclosing covers which should be of the weatherproof ventilating pattern, designed so as to interfere as little as possible with the cooling of the motor.

The covers, however, should be opened readily to admit of frequent examination of the windings with a view to prevent accumulation of coal dust. Totally enclosing covers admitting of no ventilation do to a great extent prevent the accumulation of dust, but interfere very considerably with the cooling, and necessitate the use of large types of machines in which the material is insufficiently utilised, with a consequent lower efficiency and higher price. Even the choice of larger types with reduced output is not always sufficient to keep totally enclosed motors within the limit of permissible temperature rise, and artificial means of cooling, such as water-jacketing of the motor cases and bearings, has to be resorted to, which still further increases the price of the motor, the complexity of working, and the running cost.

There is, however, a practical difficulty in regular inspection, examination, and cleaning of a motor with enclosing covers of any kind in the negligence or carelessness of the average attendant, who

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will not take the trouble to open up his motor every day for the purpose, whereas it is not nearly so difficult to get him to clean up and blow out an open-type motor regularly—firstly, because there is less trouble involved; and secondly, because the inspecting official is more likely to notice any default on his daily rounds.

Article 38 (Section V., Motors) provides that in any place where General Rule No. 8 applies a reliable apparatus for the detection of firedamp shall be provided, and immediately an indication of firedamp appears the person in charge of the machine shall immediately cut off the current and report the matter to an official of the mine.

This, no doubt, would also apply to special chambers separately ventilated with intake air when located in such district, even if only as a precautionary measure, to indicate whether or not the ventilation of the chamber were working properly. The question therefore arises whether the motor should also be provided with any special protection as a further precautionary measure to prevent danger in the case of the presence of firedamp not being noticed soon enough, and in consequence the motor not being stopped in accordance with the rule. In general, I am of the opinion (which I believe is shared by the majority of engineers) that such measures are not necessary. It is very unlikely that a defect in the windings, with consequent burning out, sparking, or arcing over to the frame, would occur without some previous warning (especially if insulation tests are frequently carried out), and the chance that such an occurrence would coincide with the unexpected presence of firedamp in the special chamber is so remote as almost to amount to a practical impossibility. The provision of totally enclosing so-called flame or explosion-proof covers would therefore appear to be *entirely unnecessary* as a precautionary measure, even should it be proved that these would be infallibly a perfect protection. As I shall show below, however, it is not at all certain that such covers form an absolutely certain protection, and by providing them one would create a false sense of security which might lead to very grave consequences.

The question, therefore, resolves itself into whether or not it is necessary to enclose any current-bearing moving contacts at which there is a likelihood of sparking occurring in service.

The probability is that the majority of such motors would be of the induction type; those working on continuous service for driving endless haulages, pumps, creepers, or fans would, if of the slip-ring type, in all probability be provided with devices for short-circuiting the rotating windings and lifting the brushes, so that the moving contacts would only be in use for a short period of time when starting up. Such motors undoubtedly do not require enclosures of any sort, as an attendant could always ascertain and avoid starting the motor if firedamp were present. Motors which require frequent stopping, starting, or speed regulation, however—*e.g.*, for main and tail haulages, staple winders, hoists, etc.—would not be provided with short-circuiting and brush-raising devices, and there would be a likelihood of sparking

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occurring the whole time they were in service. Even for such cases, however, no hard-and-fast rule for enclosing can obtain. The advisability of enclosing such slip-rings would depend on local conditions, which determine the degree of possibility or probability of the unexpected presence of firedamp in the chambers.

For all motors with their apparatus and accessories located in positions where General Rule 8 applies, and which are not in chambers separately ventilated with intake air, the rules call for total enclosure, and it therefore only remains to investigate from experience gained how far such means afford protection, and to what extent this protection should be applied to cases above discussed where the total enclosure is not actually required by law.

Experiments were carried out for the purpose of determining the value of totally enclosing as a protection against explosion at the time of the special committee on the use of electricity in mines, and details of these experiments are contained in the minutes of evidence published in 1904, upon which the report and recommendation were based. Exhaustive experiments with the same object were also commenced on the Continent about the same time, and extended into 1905. The results of these experiments not only confirm those arrived at by the special committee, but thanks to the well-planned and methodical manner in which they were executed, give a large amount of most valuable additional information bearing on the subject.

I propose to give a short account of the results of these tests, and in doing so I do not lay any claim to originality.

So far as I am aware, however, no account of these has been published in this country in a readily accessible form, and I believe there is still a large number of engineers interested in this branch of the subject who have no knowledge of these experiments. This is, therefore, my excuse in putting before you what may appear to some of you as ancient history.

The trials in question were carried out conjointly by six of the leading electrical engineering firms in Germany and the Committee of the Westphalian Mining Fund, who kindly placed special experimental galleries at their disposal and bore a share of the expenses.

In these galleries the apparatus to be tested was operated in explosive atmospheres, both of air and actual firedamp, and of air and fine coal dust. The firedamp was drawn from a disused working of the mine on which the galleries were built.

The trials were divided into three distinct series :—

1903.—Tests of special apparatus and machines submitted by the firms concerned.

1904.—Tests to determine suitable means of protecting apparatus and machinery to avoid explosion.

1905.—Tests on motors provided with the protection.

The tests of 1903 showed that practically all the protective devices

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fitted to motors proposed were either insecure and a positive danger in an explosive atmosphere, or ineffectual for mechanical or electrical reasons. Such, for example, were enclosing of complete motor with wire gauze or solid covers, enclosing of overhung slip rings in solid so-called gas-tight covers, or immersion of slip rings in oil. So far as the totally enclosing of the complete motor or of the slip rings was concerned, it was found practically impossible to prevent the entrance of explosive mixture into the interior, especially if the motor were frequently started and stopped with consequent alternate heating and cooling of the enclosed gases.

If sparking occurred in the service of these motors, an internal explosion occurred, which generally either blew the enclosing covers off, otherwise damaged the motor casing, or expelled flames and ignited gases through the bearings and oil wells, thus in most cases communicating the explosion to the surrounding atmosphere. It was found, however, that if gaps were provided of a certain size, *i.e.*, not too small to prevent the egress of the heated gases and cause a dangerous rise of pressure, and not so large as to allow free passage of the burning gases, the communication of the explosion was avoided.

The covering of the openings with wire gauze (even with two layers) was not found altogether satisfactory. In many cases this may have been due to the too coarse mesh which had been provided, but generally it was found that the gauze did not offer sufficient cooling surface relatively to the large volume of gas enclosed to prevent its being raised to a dangerous temperature, and finally allowing the explosion to be communicated to the external atmosphere. A curious phenomenon was observed with this method of enclosure which also tended to render the protection ineffective: the continued combustion inside the motor of firedamp after the first explosion had ignited it. As combustion proceeded, the hot products were carried off through the gauze at the top of the motor, and fresh firedamp was introduced below to take its place and thus feed the flame. The consequence was that the gauze was soon raised to a very high temperature and destroyed, and an explosion took place in the gallery.

A further disadvantage of this class of motor is an electrical one, due to the very small amount of ventilation which the fine-meshed gauze required permits, in deference to which it is necessary to design the motor practically on the same lines as a totally enclosed one, so that the electrical characteristics are not of the best, and the motor is large, heavy, and high in price.

In the case of slip-ring motors the immersion of the slip rings in oil was found to cause difficulties of an electro-mechanical nature, which entirely precluded their employment.

In consequence of the negative results of these trials, the second series of experiments (of 1904) was undertaken. In the first place, the nature of the explosion was studied, and how this depends

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on the volume of gas, quality of the mixture, configuration of the enclosing casing, and position of the origin or point of ignition. In particular, observations were made on the extent to which the nature of the explosion was modified by introducing partitions with orifices and other obstacles.

When a mixture of firedamp and air is exploded in a closed vessel free of internal obstacles, the maximum pressure of the explosion is about 6½ to 7 atmospheres when the volumetric percentage of methane is about 7 to 8 per cent., the pressure being attained about ⅕ of a second after ignition. With a smaller or larger percentage, not only is the maximum pressure less, but the explosion takes place at a slower rate, *e.g.*, with about 5½ per cent. of methane the pressure rises to about 3½ atmospheres, the maximum being reached in about ½ second, while with about 13½ per cent. methane the maximum pressure is only about 4 atmospheres, this being reached about 1 second after ignition.

Experiments with various sizes of containing vessels showed that the actual rate of explosion depended to some extent on the shape and volume, but the maximum pressure was practically independent of these variants.

This, however, does not apply if obstacles are introduced which materially alter the configuration, nor to two vessels communicating with one another through a small aperture. If ignition takes place in one of the two vessels, the pressure in the second may rise to much more than 7 or 8 atmospheres. In some cases it was found to rise to as much as 12 atmospheres.

This is of the greatest importance in designing enclosed apparatus for mining purposes, and shows that the designer must under all circumstances avoid apparatus enclosed in several separate compartments communicating with one another through small apertures, *e.g.*, a case containing a switch and fuse in separate compartments, with small holes between the two through which the electrical connections pass. At first sight the statement might seem paradoxical that the more gas-tight the lid of such a case fits the greater is the danger if an explosion does occur inside. A test on such a switch and fuse box, however, proved this conclusively. Each compartment A and B was closed with a separate lid held in place with four screws. When tested by exploding an explosive mixture in each compartment separately, the apertures being closed with tight-fitting plugs, no adverse results were observed; when both compartments were filled with an explosive mixture, however, and the plug in one of the apertures in the dividing partition was removed, on igniting the mixture in compartment A a violent explosion occurred which completely wrecked compartment B, and that notwithstanding that the lid of A was not a tight fit, but allowed some of the gas to escape round its edges.

A similar result was observed in an enclosed 3-phase motor with slip rings enclosed in a separate casing outside the bearing. The motor casing was provided with several small openings covered with fine gauze, while the slip-ring casing was provided with a so-called

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labyrinth seal, the function of which was to prevent a serious rise of pressure in case of an explosion—in fact, to act as a sort of safety-valve. The motor was run in an explosive atmosphere (in the trial gallery), and after running some time the gas in the motor casing was artificially exploded to simulate the effect of an earth or short circuit. A violent explosion occurred in the gallery, and it was found that the casing of the slip rings had been blown off, the 47 rivets, 3 mm. ϕ, being torn asunder. The explosion in the motor casing had been communicated to the gas in the slip-ring casing through the oil well of the bearing, the high pressure generated in the motor casing, notwithstanding the gauze-covered openings, being sufficient to force the oil out of the oil well and drive the ignited gas into the slip-ring casing, igniting the mixture there with the above-described results. Owing to the explosion taking place there under pressure, it was much more severe than it would have been under ordinary circumstances, so that the safety-valve arrangement above described was no protection.

Owing to the difficulties of building motors and other electrical apparatus actually gas-tight, *i.e.*, in which there is no communication between the inside and the surrounding atmosphere, and the observed fact that an explosion can take place in a box with a badly fitting lid without communicating itself to the surrounding atmosphere, a series of experiments was undertaken with a view of studying this phenomenon. It would hardly be within the scope of this paper to give the details of these experiments; suffice it to say that with a very explosive mixture of about 9 per cent. methane an explosion can take place within a vessel with a comparatively large aperture, without the surrounding gas being ignited by the flame issuing from the aperture; with a greater or lesser proportion of methane the danger of igniting the surrounding gas increases, and the limiting size of aperture for safety decreases. The immunity from external explosion also depends on the distance of the point of ignition from the aperture; the nearer the point of ignition to the aperture the greater the danger of external explosion. This immunity from external explosion depends on two factors—the so-called "expansion action" and the time element. Experiments have shown that an explosive mixture of firedamp ignites at a minimum temperature of about 650° C. It must be exposed to this temperature for about 10 seconds, however, before ignition takes place. The hot gases issuing from the casing at a high-pressure expand, and in so doing cool themselves below the temperature of ignition of the surrounding gas. If the pressure of explosion in the casing is high enough, the hot gases issue at such a velocity that the duration of exposure to the surrounding mixture through which they are ejected is not sufficient to cause ignition before they are cool. The results of these experiments may be summarised as follows:—

1. The maximum pressure developed in a vessel of moderate capacity by an explosion of accumulated firedamp is about 6·5 atmospheres. If in the inside of the vessel small portions are divided off by internal objects, and the compartments thus formed communicate with one

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another through comparatively long and tortuous passages, some portion of the enclosure may be exposed to a pressure of 8 atmospheres. Moreover, if the interior is partitioned off into large spaces communicating with one another through small apertures, according to the size and number of these compartments, internal pressure may be developed which no practicable method of enclosure can be made to resist. In mines of very great depth the internal pressure is proportionally higher.

2. Small openings, such as narrow gaps or fine slits in the enclosure, are not dangerous. The larger the area of opening, the less effective is the enclosure, and especially so if the aperture does not expose cooling surfaces to the gas in its passage through it. Moreover, it is less effective the nearer the point of ignition is to the aperture, and the danger increases inversely with explosiveness of the gas. An enclosure which is not gas-tight, or one with openings, is generally safe if the pressure of the ignited gas rises to 1·1 atmosphere or more before flames are expelled.

It was further found on extending these experiments to motors that the rotation of the rotors modified considerably the effects produced. Thus an enclosing cover of the slip rings of an induction motor was found to be perfectly safe with an opening of 60 sq. mm. in all kinds of gas when the motor was at rest. When the motor was running, however, with a hole of 100 sq. mm., the internal pressure of explosion rose so high as to burst the cover off and cause an external explosion, while in subsequent trials with a still larger opening, although the internal pressure remained within safe limits, yet the flames issuing through the opening caused an external explosion. The rotation, therefore, appeared to increase the pressure and rapidity of the explosion. In another case a totally enclosed continuous-current motor had holes of 8 mm. diameter drilled through the covers. When stationary, 16 holes with an area of about 800 sq. mm. together were found safe ; while with 20 holes, with an area of 1,000 sq. mm., an external explosion occurred. When running, 32 holes (1,600 sq. mm.) were still safe ; but with 34 holes (1,700 sq. mm.), an external explosion took place. Although then an enclosing cover with apertures in it may, under certain circumstances, be an effective protection, it cannot be relied on in every case, as its efficacy depends on the composition of the gas, the position of the point of ignition relatively to the aperture, and to the state of motion of the rotating parts—all of which, and particularly the last factor, may influence the effect of an explosion in a manner which cannot be determined *a priori*. Under the most favourable circumstances, moreover, the maximum safe area of the openings is small, so that a motor would have to be designed practically with the characteristics of a totally enclosed motor. In order to increase the effectiveness of this method of protection, the labyrinth enclosure was proposed. This consisted of two or more perforated covers placed one in front of another and arranged with the apertures in adjacent covers staggered so that the gases had to pass some distance over the surface of the covers in passing from one opening to the next, whereby

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it was hoped that some of the heat would be extracted by the metal covers. Although by this means the size of the openings could be made much larger than in the case of the single cover, it was still found that the results of an explosion inside depended on the same factors, and only in the case of the point of ignition being in close proximity to the opening could any cooling effect be noticed. Similar results were found to occur with the use of tubes in front of the openings, in passing through which it was hoped that the gases would be cooled. All these methods of protection were thus found to be unreliable, and had to be discarded.

In order to combine the advantages of a ventilated motor with a reliable flame-proof protection, a series of experiments was carried out to test the efficacy of wire gauze, the utility of which in the case of the Davy lamp has stood the test of time. Steel, copper, and brass wire gauze were used in the tests, having 144 square openings to the square centimetre, with wires 0·35 mm. diameter, in which the openings cover about one-third of the total area. They are practically the same dimensions as employed in the safety lamp.

In the first place, the material of the gauze did not affect the result to any appreciable extent. As in the case of covers with apertures, it was found that the protection depends on the position of the point of ignition of the gas, and is also influenced by the configuration of the internal parts and the state of motion of the rotating parts. The effects of position of points of ignition were found to be entirely the reverse of the effects in the case of the enclosure with aperture. The danger of an internal explosion being communicated to the outside increased with the distance of the point of ignition and depended directly on the explosiveness of the gas. There appeared to be a relation between the minimum area of the gauze and the volume of the vessel. By adding layers of gauze (with a small intervening space between adjacent layers) the total minimum efficacious area of gauze is reduced. Thus for a certain vessel a single layer of not less than 455 sq. cm. was required, a double layer of $2 \times 176 = 352$ sq. cm. was sufficient, and a triple layer of $3 \times 41 = 123$ sq. cm. was still quite safe. By increasing the number of layers the ventilation is seriously impaired, while a single layer is very liable to mechanical injury, which might impair its mechanical strength. When gauze protection is used it is of the utmost importance that no other openings or gaps are present, such as might occur through a badly fitting joint, as thereby the protection would be subverted. Even a hole in the gauze, caused by the removal of the little cross between four holes, was found to be sufficient to impair its efficacy and cause an explosion. A gap round a cover of 1 mm. width was found to be a source of danger. A gap not exceeding $\frac{1}{2}$ mm. width and 50 mm. deep was found to be safe, as the hot gases, in passing the 50-mm. surface, were cooled sufficiently to prevent danger.

One of the greatest disadvantages of gauze protection was found to be the "burning" mentioned before, which although in most cases not

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sufficient to damage the windings, yet was enough to cause local heating and final destruction of the gauze at those points, with a consequent explosion.

From the observed fact stated above, that slits or gaps of not more than 0·5 mm. width and about 50 mm. depth are not sources of danger, finally a form of protection was devised which embraces all the advantages of gauze without its defects. It is the so-called "plate" protection. It possesses mechanical strength, permits of ventilation, prevents an explosion by cooling the issuing gases, and is not damaged by after burning should this phenomenon take place. It consists of a series of plates, usually $\frac{1}{2}$ mm. thick and 50 mm. deep, placed side by side at a distance of $\frac{1}{2}$ mm. from one another in openings of the motor or apparatus casing. These plates are usually in the form of rings or hollow squares, but they can be any shape or size. Any number can be used, according to the amount of ventilation required, and the protection secured is independent of the position of the point of ignition, the relative volume of the containing vessel to the area of opening and of the composition of the gas.

Summarising the above observations, it can be stated that of all the various methods proposed as protective devices, the use of a labyrinth enclosure, an enclosure pierced with pipes, and the so-called flange enclosing are totally unreliable as protective devices, and must be rejected as unsafe.

On the other hand, the complete enclosure, the enclosure in wire gauze and the "plate" protection, afford reliable methods of protection, and can safely be adopted when suitably applied. To these must be added oil immersion.

So far as the total enclosure is concerned, this method of protection is mainly available in cases where internal ventilation is not essential in order to carry off the heat generated in the apparatus. Apparatus or machinery in which heat is generated is, generally speaking, therefore, not suitable to receive this method of protection. In order to be effective, the complete enclosure has to be made very strong indeed, entailing considerable weight and initial cost. On the other hand, this method of protection provides a safeguard against external mechanical injury as well as against internal explosion, and it must be remembered that it is almost a practical impossibility to make any enclosure so perfectly gas proof as to entirely prevent an explosive mixture collecting in the interior, unless it is absolutely physically enclosed (as by soldering or welding). This method of enclosure is therefore mainly applicable to switch-gear, junction boxes, and very small motors.

The protection by means of wire gauze permits of ventilation, and in this respect affords an advantage over a total enclosure. Wire gauze, however—which must be doubled to be safe—is very liable to mechanical injury, which would easily destroy its protective qualities. It must therefore be further protected by a mechanical safeguard.

The plate protection affords ample ventilation, and at the same time

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sound mechanical protection, and should therefore be considered as the most suitable enclosure for all motors.

The protection by oil immersion is difficult of application to machinery which is in constant motion—*e.g.*, the slip rings of 3-phase motors. It is therefore mainly applicable to switchgear in which sparking would otherwise occur in the ordinary course of service. It can with advantage be combined with plate or gauze protection.

In applying any of the methods of enclosing above mentioned, particular care should be exercised in the design of the machinery or apparatus to prevent any communication between large spaces through passages or apertures, where such communicating spaces might give rise to the development of exceedingly high internal pressure in case of an explosion occurring.

As far as possible, therefore, the electrical apparatus which is installed underground, and especially larger motors driving pumping plant, main and tail or endless haulages, winches, hoists, creepers, etc., which can be grouped close to the pit bottom, should be placed near the downcast shaft in the neighbourhood of the main airways; or if in the neighbourhood of the upcast shaft, in separate chambers specially ventilated with intake air, so as to avoid the necessity of any special protective device against explosion.

Where, however, this is not possible, so that the motors and the switchgear must be placed in locations coming within the provisions of Rule No. 8 of the Coal Mines Regulation Act, then as far as possible plate protection should be provided on the motors, the windings being enclosed in one enclosure, and any part (such as slip rings) in which sparking is liable to take place in service should be enclosed in a separate enclosure, particular care being exercised to prevent any communicating passages between the two enclosed spaces, total enclosure being only adopted in the very smallest motors.

The switchgear should be of the enclosed type, either total or protected by "plate" protection or gauze, preferably with oil break switches and cartridge fuses, and with no possibility of an explosion in one compartment being communicated to the gases in any other.

I trust that these few notes will induce other members to give the results of their experience and express their views, and that the resulting discussion may be another step in the direction of determining the correct lines of development of electrical apparatus for use in collieries.

Discussion.

Mr Mavor. Mr. S. Mavor: I entirely agree with the general view of the subject taken by the author. We should not exaggerate the risks attendant on the use of electricity in fiery mines, and we should do everything in our power to reduce them to the vanishing point or at least to a minimum, and Mr. Simon has shown what can be done to meet the conditions so far as motors themselves are concerned. What has been done is no doubt a great testimonial to the general

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Mr. Mavor.

safety where electricity has been applied, although I am not sure that I can go so far as Mr. Simon does in supposing that no serious mishaps have occurred. I am sorry to say a few have come to my notice which I have no doubt were due to the use of electricity. I think in this country we ought to have had more guidance from the Home Office with regard to rendering motors as safe as possible against explosive gas. As the author pointed out, experiments were made in the year 1904, the year before the appointment of the Home Office Committee on electricity in mines. At Woolwich there is a specially constructed gallery for making tests in explosive atmosphere; this is suitable for testing electric apparatus. Further investigations are urgently required, and should be conducted. It is rather extraordinary that the results of so very important a series of experiments made in Germany four or five years ago should only now have been made common property of engineers in this country, who have been obliged to use their independent judgment in rendering the apparatus safe for practical purposes and have been without such valuable information as the author now gives us. The paper is full of most useful points, such as the importance of isolating enclosed chambers from each other. Some time ago I made a practice of hermetically sealing the communication between the switch and fuse boxes in mines, because it seemed to me that the smaller the volume of contained gas, the less the risk of bursting the box. One extremely important point which has not been touched upon is the necessary ratio of the area of vent to the volumetric capacity of the enclosed motor or switch box. That is the point upon which I would ask Mr. Simon to give us some supplementary information, and I should be glad to know if a motor has ever been experimented on in that way, and whether we can have his assurance that the motor he describes has sufficient vent area. I have for some time used three or four sheets of gauze with a strong cast-iron grid above, but in these motors I should hardly advise that. In motors about 70 or 80 H.P. I have given a foot and half square, but that may not be sufficient, and it would be a great advantage to manufacturers if the Home Office would say whether it is or is not, which they might well do, with all the facilities that they have at Woolwich to test such motors. There is also the difficulty that coal-cutting machines admit dust into their interiors, and hitherto I have completely enclosed coal cutters, but I have not been quite happy about it, because in the event of an explosion taking place a cover may be blown off, or something sufficient to allow an escape of gas. A coal cutter is necessarily under the immediate charge of a man who ought to be somewhat above an average collier in intelligence, and in a fiery mine he has to use a lamp which gives an indication of danger by showing a blue cap on the flame, and whenever it does so he will stop the machine till the gas is swept out and ventilation improved. There is one point in the paper which I think is hardly clear, and I would like to ask whether I understood Mr. Simon to say that an explosion in a motor might take place

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Mr. Mavor. and the flame might find egress without igniting the surrounding gas, owing to the cooling effect of the expanding products of combustion.

Mr. Stevenson. Mr. G. STEVENSON: In the first place, I would like to emphasise a statement made on page 199, namely, that periodical inspection and cleaning should be enforced as a preventive. I have had some little experience in mining work, and I know what a great deal of cleaning goes on and what pride men take in their plant in regard to its working and general appearance. At the same time, it is hardly necessary, as Mr. Simon suggests, to have white tiles on the floors in order to make the men take an interest in their work. I find that with the common staff employed in a mine, if the men are given good plant to start with they take a great interest in it. The author has referred to the question of cables. He deals principally with electrical plant in mines, but I presume that cables come under this category, and I should like to hear his views on the cable question. There is another type of motor to which he has not referred, and which I believe could be used in some cases, with fan device inside and an opening for a pipe at the commutator end, also another opening at the pulley end. It is sometimes necessary to place the motor in an up-cast shaft, and where this has to be done it would be a simple matter to use this type of motor, as a supply of fresh air could be obtained by leading pipes through to the down-cast shaft. I do not claim that such a type of motor could be used in all cases, but there are cases where it could be applied, and I would like to hear what the author has to say on that point. With regard to this special plate protection, I would like more information. For instance, it may be all right when the plant is first put down in a mine, but when you come to open up a motor and take off these plates how do you make your joint connection so that the arrangement will be perfectly flame-tight? Another thing I would like the author to tell us, is the effect produced on the rating of a motor by putting on these plates. How much would the output be increased, as compared with the same machine totally enclosed? This, of course, is a very important point from the manufacturer's point of view. At the top of page 206 the author mentions an arrangement of tubes in front of the opening, but I do not quite follow that, and I would like him to make the arrangement more clear. Turning to the question of motors generally, I think that the whole paper tends to support my views relative to the use of squirrel-cage *versus* slip-ring machines, and if I had anything to do with fiery mines I would certainly attempt to make arrangements for using the former type wherever possible, as slip-rings and brushes are altogether objectionable. As to the question of switches and fuses, I have no confidence in air-break switches. I believe that the best switch is undoubtedly the oil-break type, and the use of this type of switchgear is the strongest argument in favour of the 3-phase system, as applied to mines.

Mr. Clothier. Mr. H. W. CLOTHIER: As a student of mining conditions I am a little disappointed that we have not had more information in the paper

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about switchgear. In the second paragraph of the paper Mr. Simon is, I think, rather too sanguine about past experience, for it is only a few weeks ago that there was an explosion in a mine in England where two pitmen lost their lives through a flame being emitted from a joint on a switch. In that case, according to the evidence at the inquest, the switch-box was provided with a joint, consisting of a ring of a small section fixed into a groove and bearing on a narrow edge, the hinge being a fixed one and with clamping screws only on the opposite side, a very common form of switch which has been so-called gas-tight and flame-proof and suitable for mines. In this particular case it would appear that the rubber jointing material was displaced and allowed the emission of a flame through the opening when the man was operating the switch. In order to obviate such dangers as that it is the practice of the firm with which I am connected to use a wide flange joint on such switches for both air and oil breaks. There is a good wide metal-to-metal surface clamped down by a number of bolts all round, and even if it is not sufficiently tightened there is no harm done, as we have what is tantamount to the plate protection. Mr. Simon has pointed to the difficulty of making an electrical apparatus gas-tight, and that is mainly because one has to have parts projecting through the case, and if there are glands at these points they are likely to be too tight and cease to operate, and so we must have clearances. The use of oil-break switches is questionable on continuous-current systems. It is generally considered that an oil break is likely to give rise to abnormal voltages when breaking on very inductive loads. I do not agree with the previous speaker, who says that he gets entire protection from explosion by the use of oil. It seems to me quite possible for a flame to protrude from an oil-break switch if the joint is not suitable, because on breaking the flame will rise up through the oil if it has a sufficient power behind it. We have seen tanks blown off with a very heavy shock, but if oil-break switches are provided with strong cases and with wide metal-to-metal machined flange joints I think we have safety for alternating-current systems. Another objection to the use of oil in places a long way from the surface is that the oil is likely to get dirty through frequent use, and replacement may be neglected. I object to plate or gauze protection as described by the author for motors on an oil switch, because it seems to me that dirt and coal dust will get through the narrow slits, and therefore for switchgear I think an attempt at total enclosure is better. It is a matter on which I would like to have the author's opinion, as he has had more experience than I have in this respect. Mr. Clothier

Mr. A. H. KELSALL: I think the oil switch is disadvantageous because of the rapid break. Mr. Stevenson was anxious for more satisfactory cleaning, and I think that is a very important point, and if more attention were paid to the question of cleaning in the design of the machine it would be of very great benefit. With regard to the gauze, Mr. Mavor has drawn attention to one way of protecting against mechanical injury, and, of course, it is an easy matter to back fine Mr. Kelsall.

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Mr. Kelsall. gauze up with a coarse mesh of gauze which offers good mechanical resistance, and several layers of fine gauze could be adopted as well.

Mr. Mavor. Mr. MAVOR: Mr. Simon referred to a gauze protection, and he spoke as if the removal of a very small portion of gauze would nullify the protection. It seems to me that these plates described in this plate method on account of their lightness might be subject to damage at one point, which by separating the plates would similarly nullify the protection offered by this method.

Mr. Robertson. Mr. J. A. ROBERTSON: I think that the general users of electricity are very much indebted to those manufacturers who have designed special apparatus to withstand the trying conditions of colliery working. We have now a type of enclosed switchgear which is very much better than anything hitherto designed for shipyards and similar conditions, and which would not have been so perfect had the designers not been called on to meet these specially severe conditions. Mr. Mavor thinks that the Home Office should carry out experiments in this country similar to those referred to in the paper, to assist manufacturers in designing suitable motors, but I gather that these experiments were carried out by a syndicate of German manufacturers and not by the German Government. Would it not be worth while for the manufacturers in this country to co-operate in a similar manner and carry these experiments a stage further? The tremendous responsibilities incurred in using electrical apparatus in coal-mines would justify almost any expenditure, and if the Government cannot be persuaded to do it the manufacturers might find that the results would justify the expense. It is interesting to find that the system of protection explained by Mr. Simon is really the principle of the old Davy safety lamp.

Mr. Clothier. Mr. CLOTHIER: With reference to the manufacturers taking up these experiments I would like to ask whether the manufacturers in Germany were supported by a Government grant in the expenses which they had to undergo.

Mr. MacKenzie. Mr. J. D. MACKENZIE: There is just one question as to the matter of coal dust choking up the openings between the plates. They are very small openings, and we all know the tenacity with which coal dust sticks to everything, and hence the probability of closing up all such openings as the author has described.

Mr. Stevenson. Mr. STEVENSON: If I might ask another question, it would be regarding those curves. In a certain percentage within certain limits the pressure rises to a very much higher extent. Could the author give us the reason for that? He stated the facts, and he might give the reasons why that should be so.

Mr. Simon. Mr. SIMON (*in reply*): Mr. Mavor said that I appeared over sanguine in what I said in the second paragraph of my paper, but at the time I wrote these notes the unfortunate accident at Stanley Colliery had not occurred, and the paper was in print when the report of that accident came to my notice. I think that, taking the general results of the investigation, it seemed proved that the explosion was due to care-

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lessness in the design or the use of the apparatus. The report I heard was that the explosion resulted from the switch being used in a defective condition. Unfortunately, the switch was so made that the blades did not leave the contacts before the cover was opened. Mr. Simon.

Mr. CLOTHIER: I hardly think that is correct. The switch was quite in good order, and the only thing that was wrong with it was the jointing. Mr. Clothier.

Mr. SIMON: Mr. Mavor said that he had already adopted the idea of enclosing switchgear in separate small cases which were hermetically sealed from one another, his idea being that by having a small quantity of gas the result of the explosion would be less. I think the experiments prove that that is not the case; on the other hand, it is easier to make a small vessel sufficiently strong to resist internal pressure than a large one, so that Mr. Mavor was certainly working on correct lines. With regard to the area of opening in a motor like the one shown, as I pointed out, this area can be made greater or less to suit the designer's own ideas. In this particular case the idea was to provide a motor of as nearly standard design as possible with this plate protection, and also to use a rotor with a standard shaft. These end shields correspond to the normal end shields, and the plate protection is made up in packets, which can be quite easily fitted inside. Mr. Simon.

Mr. STEVENSON: How do you get at the motor for cleaning purposes? Mr. Stevenson.

Mr. SIMON: You have to blow it out through the plate or take off the end shields. The motors which have been tested have proved satisfactory, but, at the same time, I don't say that I would guarantee that such a motor would not cause an explosion. In designing any apparatus of this kind one does the best one possibly can without necessarily giving a guarantee. I have no doubt that Mr. Mavor's motor with the gauze would also prove effective, although I question whether Mr. Mavor would guarantee it under all circumstances. So far as coal-cutting machines are concerned, they have usually comparatively small motors, and the best protection is to make them strong enough to stand high pressures in case of an explosion occurring inside. Mr. Simon.

Mr. MAVOR: I am not sure whether you have discovered the existence of any relation between the gauze and the volume of gas. Mr. Mavor.

Mr. SIMON: There was a relation established in the case of gauze covering between the area of gauze and the total volume of the enclosed gases. During the trials it was found that an explosion in a motor or other vessel might take place, and the flame might find egress without igniting the surrounding gas, owing to the cooling effect and expanding of the products of combustion in their egress out of the chamber. Mr. Stevenson asked whether it would be possible to have a self-ventilating motor in a mine. I should think that idea a very good one if it did not involve too much expense in carrying fresh-air pipes to and from the motor. Such motors have been used extensively Mr. Simon.

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Mr. Simon. in textile work, where very often they are arranged to draw fresh air from the duct and discharge the heated air to a return air duct in order to prevent over-heating of the workrooms, and I do not see why a similar arrangement could not be made in a mine, provided the expense were not too great. Care would need be taken that the jointing of the pipes was sufficiently tight to prevent any gases being sucked into and carried through the motor. Mr. Stevenson also mentioned the question of cables. I thought it would be going too far to include cables as well as other apparatus in these notes, and besides that, both the method of laying cables and the class of cables to be used are laid down pretty decidedly in the rules for electricity in mines. I think from these rules it is necessary, when using high and medium pressure, to have the whole of the cables enclosed in a continuous covering of metal which is earthed, and where such is used I think it is advisable in every case to provide the motor and the switch-cases with metal end boxes which are actually screwed or attached to the motor or switchgear, so that all the electrical conducting parts are enclosed in a thoroughly mechanical manner. As to the effect of plate protection on the rating, a motor of the open type, giving 30 H.P., would be reduced to about 24 H.P. by the additional protection as illustrated; but, of course, if the motor were built specially with a larger number of openings the reduction in the output might be less. It is practically the same as that due to the alteration from an open-type motor to a ventilating enclosed motor. I mentioned the use of tubes in front of small apertures, and by that I mean tubes so arranged in front of the openings that the products of internal combustion must pass through these tubes into the air. These were tried, it being thought that they would offer sufficient surface to the hot gases in their passage through them to lose their dangerous temperature, but it was not found effective. I think there is a great deal to be said for the squirrel-cage motors in the fiery parts of mines, but there are a great many classes of work in collieries where the squirrel-cage motor is unsuitable. For example, I cannot see where in the case of a main haulage gear, or a staple winder, or a hoist of large size, the squirrel-cage motor could be used with advantage, especially if a certain amount of speed regulation were required. With regard to the oil-break switches, Mr. Clothier and Mr. Kelsall mentioned that they did not consider immersion in oil sufficient protection. I tried to emphasise that in my paper too, because I have had experience of cases in which explosions have occurred inside oil vessels in consequence of the decomposition of the oil, and therefore it is best, even where oil immersion is used to extinguish the spark, to have the switchgear further enclosed either in a solid enclosure or in one with gauze or plate protection. The solid enclosure must be made very strong indeed, in order to resist any internal explosion which might occur through the flame rising above the surface of the oil, and therefore an enclosure fitted with gauze or plate protection would be more likely than the solid protection to allow the heated gases to escape without

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Mr. Simon.

shattering the enclosure. The continuous-current switch with oil immersion is not so effective as the alternating current, and should be avoided as far as possible. I think, therefore, that as far as underground working is concerned, especially where there is a liability to sparking and a danger of explosion, perhaps on this account as well as on the question of commutators, the 3-phase current is preferable to the continuous current. Mr. Stevenson, as I understand the question, asked the reason why the explosion should take place so much more rapidly when the air is mixed with 8 or 9 per cent. of methane than at any other percentage. That amount of methane represents the quantity which combines entirely with the oxygen in the air, while in the case of a smaller or larger quantity of methane there is a surplus of oxygen or methane that may account for the more rapid combustion and consequently the higher pressure, and it would also account for the somewhat higher temperature owing to the larger quantity of heat that would be developed; there would also be less gas to heat up to the final temperature which would lead to more violent explosion. The only other question was as to the choking of the plate with coal dust. Wherever there is coal dust this danger is met with, and that is why I laid such special stress on the advantages of periodical cleaning, and, if possible, placing the motors as far as possible from places where coal dust abounds. I do not actually advocate tesselated pavements, but I have seen mines with a doormat at the entrance to the pumping chamber, which visitors were solicited to use before entering, in order to keep the chamber with the electrical machinery contained in it scrupulously clean and in perfect condition. In reply to Mr. Clothier, so far as I am aware the whole of the cost of the experiments was borne by the manufacturers and the representatives of the mining interests. The German Government did not support the experiments by a grant.

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INVESTIGATIONS ON THE ELECTRICAL STATE OF THE UPPER ATMOSPHERE.

By W. MAKOWER, M.Sc., MARGARET WHITE, and E. MARSDEN.

(*Paper read at Manchester on April* 20, 1909.)

The investigation made during July and August, 1908, is chiefly concerned with the measurement of the electric currents flowing from a kite down the wire by which it is attached to the winding machine. In the first experiments different lengths of wire were let out with the kite, detached from the winding machine, and the free end of the wire attached to an ebonite insulator fixed to the ground. The kite was then connected to earth through a sensitive dead-beat galvanometer and the current measured. In these experiments the currents at considerable heights were so large that it was found necessary to reduce the sensitiveness of the galvanometer by shunting. The plan was therefore adopted in later experiments of using a portion of the kite wire when attached to the drum of the winding machine, which was earthed, as a shunt, and thus making use of the usual daily flights taking place at the Glossop observatory. The mean currents obtained are given in the accompanying table :—

Height of Kite above Ground.	Current in Amperes.
2,000 feet	5×10^{-5}
4,000 ,,	13×10^{-5}
6,000 ,,	23×10^{-5}

The current at any fixed height varied considerably from day to day. There seemed, however, to be a fairly close connection between the current and wind velocity, the currents being great when the wind was high. A few experiments have been made on the potential of the air at different heights, but no very reliable results have yet been obtained on account of the difficulty of satisfactorily insulating for the high potentials to be measured.

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ORIGINAL COMMUNICATION.

DIMENSIONS OF SINGLE-PHASE CORE AND SHELL TRANSFORMERS, WITH COPPER AND IRON CIRCUITS OF UNIFORM RECTANGULAR CROSS-SECTION.

By A. R. Low, Associate Member.

(*Received July 22, 1908. Revised July 7, 1909.*)

Section 1.

Symbols used

$P_o = \frac{I}{2}$ (input and output).

p_i = Iron loss as percentage of P_o.
p_c = Copper loss as percentage of P_o.
f_i = Iron space factor.
f_c = Copper space factor.
d_i = Flux density in lines $\times 10^{-4}$ per cm.^{2} $\left(\frac{B}{10000}\right)$ (average value).
d_c = Current density in ampere lines per mm.^{2} (average value).
w_i = Watts per kg. iron loss (average value).
w_c = Watts per kg. copper loss (average value).
N = Frequency in cycles per second.
l_i = Price of iron in £ per kg.
l_c = Price of copper in £ per kg.
x = Window width ...
y = Core width ... ...
z = Window height ...
u = Depth of laminations
} For a core transformer, the dimensions being in decimetres.

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If we make the substitution $\begin{pmatrix} y & x & u & z & 1 \div m'' & m' \\ x & y & z & u & m' & 1 \div m'' \end{pmatrix}$ throughout, the results obtained apply where—

x = Core width ... ...
y = Window width ...
z = Depth of laminations
u = Window height ...

} For a shell transformer.

Further—

$$h = 11 \cdot f_i \cdot f_c \cdot d_i \cdot d_c \frac{N}{50}.$$
$$g_i = 2 \cdot 7, 7 \cdot f_i \cdot w_i.$$
$$g_c = 2 \cdot 8, 9 \cdot f_c \cdot w_c.$$
$$k_i = 2 \cdot 7, 7 \cdot f_i \cdot l_i.$$
$$k_c = 2 \cdot 8, 9 \cdot f_c \cdot l_c.$$
$$4 F^4 = \frac{\pi}{4} c^4 = \frac{P_o}{h}.$$
$$a = \frac{g_i}{10 \cdot h \cdot p_i}.$$
$$b = \frac{g_c}{10 \cdot h \cdot p_c}.$$
$$m' \cong \frac{1}{2} \pi.$$
$$m'' \cong \frac{4}{\pi}.$$
$$m = \frac{m' + m''}{2}.$$
$$M' = \frac{b}{a} m'.$$
$$M'' = \frac{b}{a} m''.$$
$$M = \frac{M' + M''}{2}.$$
$$L^2 = \frac{a}{b} \frac{c^4}{a^4}.$$

The transformation is employed—

$$x = a X \qquad z = a Z$$
$$y = b Y \qquad u = b U.$$

Section 2.

The following expressions may be written down :—

Effective iron cross-section ...	$= f_i \cdot y \cdot u$ dm.^{2}.	
Mean iron circuit ...	$= 2 (x + z + m' y)$ dm.	
Volume of iron ...	$= 2 \cdot f_i \cdot y \cdot u (x + z + m' y)$ dm.^{3}.	
Weight of iron... ...	$= 2 \cdot 7, 7 \cdot f_i \cdot y \cdot u \cdot (x + z + m' y)$ kgms.	
Total iron loss	$= (2 \cdot 7, 7 \cdot f_i \cdot w_i) \cdot y \cdot u \cdot (x + z + m' y)$ wts.	
	$= g_i \cdot y \cdot u \cdot (x + z + m' y)$ watts.	

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Effective copper cross-section $= f_c \,.\, x \,.\, z$ dm.^{2}.

Mean copper circuit ... $\ldots = 2\left(y + u + \frac{x}{m''}\right)$ dm.

Volume of copper ... $\ldots = 2 \,.\, f_c \,.\, x \,.\, z \,.\, \left(y + u + \frac{x}{m''}\right)$ dm.^{3}.

Weight of copper ... $\ldots = 2 \,.\, 8,9 \,.\, f_c \,.\, x \,.\, z \,.\, \left(y + u + \frac{x}{m''}\right)$ kgms.

Total copper loss ... $\ldots = (2 \,.\, 8,9 \,.\, f_c \,.\, w_c)\, x \,.\, z \,.\, \left(y + u + \frac{x}{m''}\right)$ wts.

$= g_c \,.\, x \,.\, z \,.\, \left(y + u + \frac{x}{m''}\right)$ watts.

The iron and copper losses are thus expressed in terms of the weight in kilograms multiplied by the watts per kilogram.

The losses may also be expressed as percentages of P_o.

$$\text{Iron loss} = \frac{p_i}{100} \,.\, 1000\ P_o \text{ watts},$$
$$= 10\ p_i\ P_o.$$

Equating this to the former expression—

$$10\ p_i\ P_o = g_i \,.\, y \,.\, u \,.\, (x + z + m'\, y) \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

and in exactly the same way—

$$10\ p_c\ P_o = g_c \,.\, x \,.\, z \,.\, (y + u + \frac{x}{m''}) \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The total flux carried by the core is—

$$f_i \,.\, y \,.\, u \,.\, d_i \,.\, 10^6.$$

The total current carried by the coils is—

$$f_c \,.\, x \,.\, z \,.\, d_c \,.\, 10^4.$$

Since the total power—that is, the sum of the input and output—is the total current multiplied by the total flux with which it is interlinked, an expression for P_o may be written down—

$$P_o = \frac{1}{2} \,.\, 4,\ 4 \,.\, 50 \,.\, \frac{N}{50} \,.\, f_i \,.\, f_c \,.\, d_i \,.\, d_c \,.\, x \,.\, y \,.\, z \,.\, u \,.\, 10^6 \,.\, 10^4 \,.\, 10^{-8} \,.\, 10^{-3},$$
$$= 11 \,.\, \frac{N}{50} \,.\, f_i \,.\, f_c \,.\, d_i \,.\, d_c \,.\, x \,.\, y \,.\, z \,.\, u \text{ kilovolt-amperes} \quad . \quad . \quad . \quad (3)$$

Section 3.

Using the values of a, b, and c[4] (1) becomes—

$$a \,.\, y \,.\, u \,.\, (x + z + m'\, y) = x \,.\, y \,.\, z \,.\, u \quad . \quad . \quad . \quad . \quad . \quad (4)$$

(2) becomes—

$$b \,.\, x \,.\, z \,.\, (y + u + \frac{x}{m''}) = x \,.\, y \,.\, z \,.\, u \quad . \quad . \quad . \quad . \quad . \quad (5)$$

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(3) becomes—

$$x \cdot y \cdot z \cdot u = \frac{c^4}{m''} \quad \ldots \ldots \ldots \ldots \quad (6)$$

After some reduction (4), (5) may be written in the form—

$$z = \frac{a\,(x + m'\,y)}{x - a} \quad \ldots \ldots \ldots \quad (7)$$

$$u = \frac{b\,(x + m''\,y)}{m''\,(y - b)} \quad \ldots \ldots \ldots \quad (8)$$

Multiplying (7) by (8) and using (6)—

$$z\,u = \frac{c^4}{m''\,x\,y} = \frac{a\,b\,(x + m'\,y)\,(x + m''\,y)}{m''\,(x - a)\,(y - b)}.$$

That is—

$$x\,y\,(x + m'\,y)\,(x + m''\,y) = \frac{c^4}{a\,b}\,(x - a)\,(y - b) \quad \ldots \quad (9)$$

Section 4.

The system of equations—

$$\begin{cases} z = \dfrac{a\,(x + m'\,y)}{x - a} & \ldots \ldots \ldots \ldots \quad (7) \\ u = \dfrac{b\,(x + m''\,y)}{m''\,(y - b)} & \ldots \ldots \ldots \ldots \quad (8) \\ x\,y\,(x + m'\,y)\,(x + m''\,y) = \dfrac{c^4}{a\,b}\,(x - a)\,(y - b) & \ldots \quad (9) \end{cases}$$

gives the fundamental relations between the dimensions of a transformer when all the other elements of design are kept constant.

This assumption may be justified by supposing that a fairly close design has been already obtained by slide-rule work, and that for the range between this design and the best dimensions the variation in densities and space factors is negligibly small.

It is seen from the system that there are three relations between four variables, and that there is therefore a onefold infinity of values of $x\,y\,z\,u$, satisfying the system.

In fact, any values of x and y satisfying (9) when substituted in (7) and (8) give values of z and u, and the values of $x\,y\,z$ and u so obtained give the dimensions of a transformer satisfying the data of design.

Section 5.

The general form of the curve is shown in Fig. 1.*

Now it is clear that $x\,y\,z$ and u must be real and positive, hence from equations (5), (6) we must have—

$$x > a$$
$$y > b.$$

* Note.—Cf. with some interesting quartics with and without oval branches discussed in Frost's "Curve-Tracing."

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It is seen from Fig. 1 that the oval branch lying beyond the straight lines $x = a$, $y = b$ is the only branch leading to positive values of $x\ y\ z$ and u.

It is therefore necessary only to consider the variation of the oval branch.

Section 6.

Let the ratio of p_i to p_c be kept constant.

It follows that $p_i \propto p_c \propto \frac{1}{a} \propto \frac{1}{b}$.

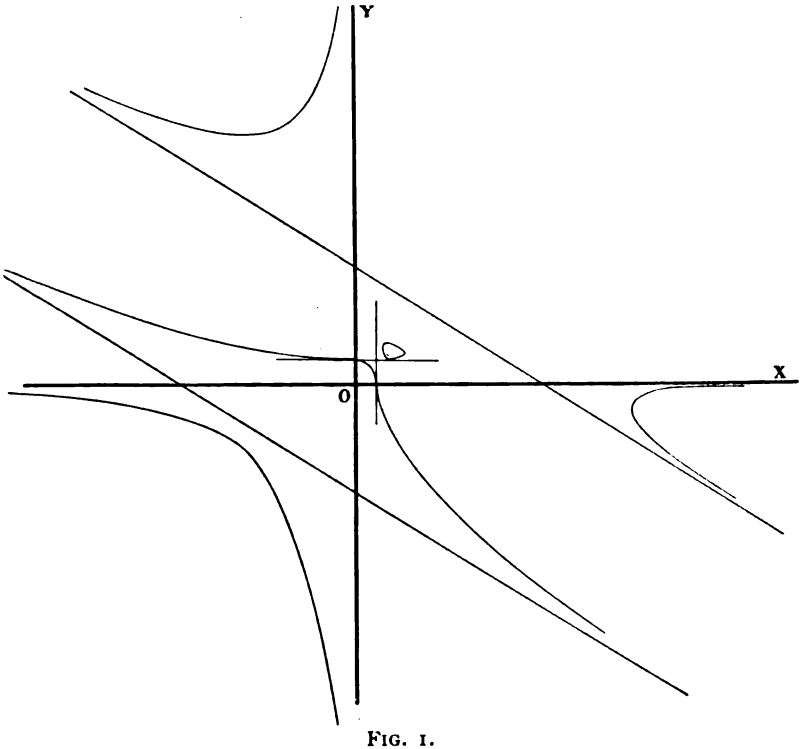

Fig. 1.

It is found that as p_i increases the oval swells until it coincides with the straight lines $x = o$, $y = o$ and the straight line at infinity, and as p_i decreases the oval shrinks until for definite values of p_i, p_c and the corresponding values of a and b it becomes a point.

No oval cuts any other oval, hence from geometrical considerations the point is a conjugate point.

This point gives unique values of x and y, from which unique values of z and u are derived by equations (7) and (8) taking the corresponding values of a and b.

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For smaller values of p_i, p_c the oval branch disappears.

The values of x y at the conjugate point and the derived values of z u constitute a unique solution of the transformer dimensions for the given ratio $p_i : p_c$ and for minimum values of p_i and p_c.

Section 7.

Let now the ratio p_i to p_c vary continuously, the conjugate point also moves continuously, tracing out a locus of conjugate points.

Finally it rises to be determined what point on this locus corresponds

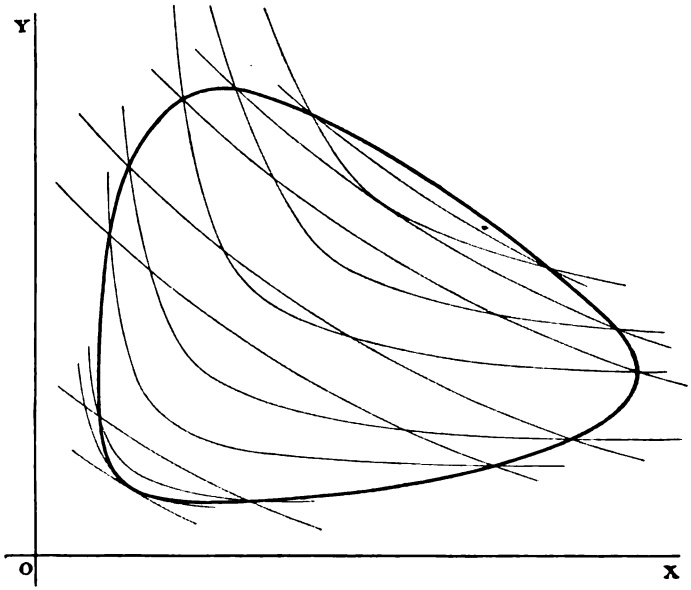

Fig. 2.

to the transformer of least cost and of least losses, independently of the ratio of p_i to p_c.

Section 8.

The analysis is much simplified by the transformation to X Y Z U.

(7) becomes—

$$Z = \frac{X + M'Y}{X - 1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

(8) becomes—

$$U = \frac{X + M''Y}{M''(Y - 1)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

(9) becomes—

$$XY(X + M'Y)(X + M''Y) = L^2(X - 1)(Y - 1) \quad . \quad . \quad (12)$$

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The quartic (12) may be conveniently plotted as the intersection of the two families of hyperbolas—

$$(X + M' Y)(X + M'' Y) = L^2 \sin^2 i$$

and—

$$X Y \sin^2 i = (X - 1)(Y - 1),$$

which reduces to—

$$(X - \sec^2 i)(Y - \sec^2 i) = \sec^2 i \tan^2 i,$$

where i is a variable parameter (see Fig. 2).

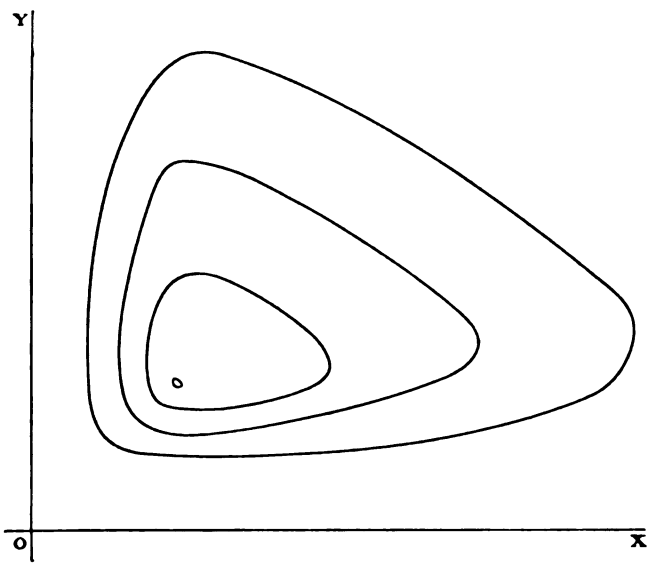

FIG. 3.

Different values of a give different values of $L^2\left(\frac{a}{b} = \text{const.}\right)$ corresponding to different ovals (see Fig. 3).

SECTION 9.

To find the locus of conjugate points we may rewrite (12), dividing by X Y—

$$V \equiv (X + M' Y)(X + M'' Y) - L^2\left(1 - \frac{1}{X}\right)\left(1 - \frac{1}{Y}\right) = 0 \quad . \quad . \quad (13)$$

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and the conditions for a singular point—

$$\frac{dV}{dx} \equiv (X + M'Y) + (X + M''Y) - L^2 \frac{1}{X^2}\left(1 - \frac{1}{Y}\right) = 0 \quad . \quad . \quad . \quad (14)$$

$$\frac{dV}{dy} \equiv M(X + M''Y) + M''(X + M'Y) - L^2 \frac{1}{Y^2}\left(1 - \frac{1}{X}\right) = 0 \quad . \quad (15)$$

Add (14) multiplied by X to (15) multiplied by Y—

$$2(X + M'Y)(X + M''Y) - L^2 \left\{ \frac{1}{X}\left(1 - \frac{1}{Y}\right) + \frac{1}{Y}\left(1 - \frac{1}{X}\right) \right\} = 0.$$

Using (13) this reduces to—

$$2\left(1 - \frac{1}{X}\right)\left(1 - \frac{1}{Y}\right) - \frac{1}{X}\left(1 - \frac{1}{Y}\right) - \frac{1}{Y}\left(1 - \frac{1}{X}\right) = 0.$$

After further reduction—

$$\left(X - \frac{3}{2}\right)\left(Y - \frac{3}{2}\right) = \frac{1}{4} \text{ (see Fig. 4)} \quad . \quad . \quad . \quad . \quad . \quad (16)$$

Since the equation is free of L^2, M', and M'' it is the locus of singular points.

Hence, noting that the lower branch passes through the point R (1, 1) at an angle of 45° with the negative directions of the axes, it is seen that only the upper branch satisfies the conditions of Section 5—

That is—

$$x > a \qquad y > b.$$

$$X > 1 \qquad Y > 1.$$

It is clear from physical and geometrical considerations that the singular points on the upper branch are conjugate points.

Dr. L. N. G. Filon has furnished an analytical proof, which is not printed here.

Section 10.

If to (14) multiplied by M' + M'' we add (15) multiplied by −2

$$(M' - M'')(X + M'Y - X - M''Y) = L^2 \left\{ \frac{1}{X^2}\left(1 - \frac{1}{Y}\right)(M' + M'') - \frac{2}{Y^2}\left(1 - \frac{1}{X}\right) \right\}$$

after some reduction—

$$\left(X - \frac{1}{2}\right)^2 - \frac{M' + M''}{2}\left(Y - \frac{1}{2}\right)^2 = \frac{1}{4}\left(1 - \frac{M' + M''}{2}\right) + (M' - M'')^2 \frac{X^2 Y^3}{2L^2} \quad . \quad . \quad (17)$$

The intersection of (17) and (16) gives the values of X Y corresponding to the given values of M' M''.

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SECTION 11.

Graphical solution of the particular case where $M' = M''$.

Equation (17) now becomes—

$$\left(X - \tfrac{1}{2}\right)^2 - M\left(Y - \tfrac{1}{2}\right)^2 = \tfrac{1}{4}(1 - M) \quad . \quad . \quad . \quad (18)$$

Curves (16) and (18) are shown in Fig. 4 intersecting in four points P, Q, R, S, of which only P lies on the upper branch of (16).

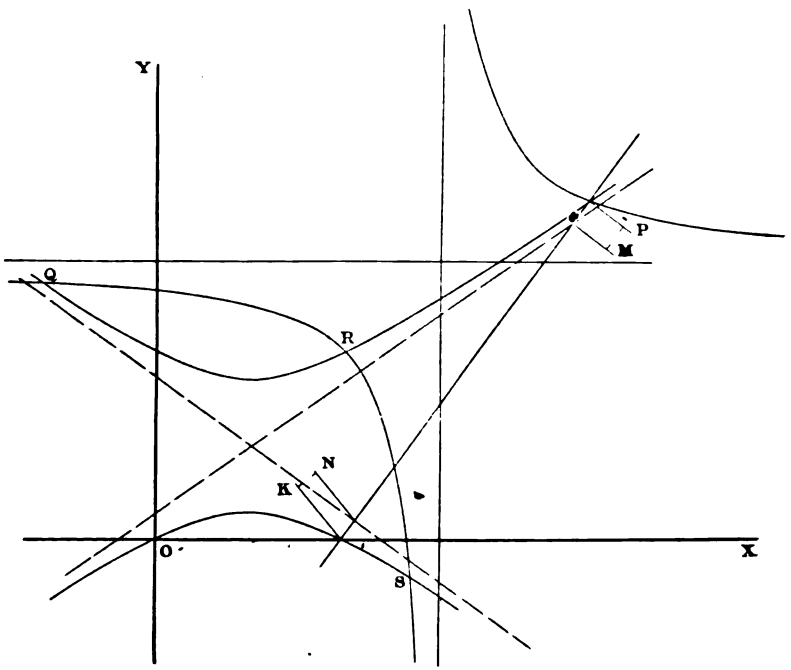

FIG. 4.

To find P without drawing (18), draw the asymptotes—

$$\left(X - \tfrac{1}{2}\right) = \pm \sqrt{M}\left(Y - \tfrac{1}{2}\right)$$

and lay a straight edge across the figure so as to make PM = KN, K being the point (1, 0).

SECTION 12

Taking X as the independent variable, Y and M may be calculated and tabulated.

Rearranging the columns, we get values of X and Y tabulated against M.

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M.	X.	Y.
12·50	4·00	1·600
12·08	3·95	1·600
11·66	3·90	1·605
11·25	3·85	1·605
10·85	3·80	1·610
10·46	3·75	1·610
10·07	3·70	1·615
9·70	3·65	1·615
9·34	3·60	1·620
8·98	3·55	1·620
8·61	3·50	1·625
8·26	3·45	1·630
7·92	3·40	1·630
7·58	3·35	1·635
7·25	3·30	1·640
6·93	3·25	1·645
6·61	3·20	1·645
6·30	3·15	1·650
6·00	3·10	1·655
5·70	3·05	1·660
5·41	3·00	1·665
5·13	2·95	1·675
4·85	2·90	1·680
4·58	2·85	1·685
4·32	2·80	1·690
4·06	2·75	1·700
3·81	2·70	1·710
3·57	2·65	1·715
3·33	2·60	1·725
3·10	2·55	1·740
2·87	2·50	1·750
2·65	2·45	1·765
2·44	2·40	1·780
2·24	2·35	1·795
2·04	2·30	1·810
1·85	2·25	1·830
1·67	2·20	1·855
1·49	2·15	1·885
1·32	2·10	1·915
1·16	2·05	1·955
1·00	2·00	2·000
$\frac{1}{M}$	Y.	X.

L^2 might also be tabulated, but it is calculable directly from X, Y, and M by means of equations (13), (14), (15), each of which should give the same value of L^2 if the graphical work or tabulation is accurate.

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SECTION 13.

From (13) and (14) by division—

$$\frac{(X + M'Y)(X + M''Y)}{X + M'Y + X + M''Y} = X^2\left(1 - \frac{1}{X}\right).$$

∴ From (10)—

$$Z = \frac{X + M'Y}{X - 1} = \frac{X\,[2X + (M' + M'')Y]}{X + M''Y}.$$

$$Z = 2X\left[1 + \frac{(M' - M'')Y}{2(X + M''Y)}\right].$$

$$z = 2x\left[1 + \frac{(m' - m'')y}{2(x + m''y)}\right] \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

From (13) and (15) by division—

$$\frac{(X + M'Y)(X + M''Y)}{M''(X + M'Y) + M'(X + M''Y)} = Y^2\left(1 - \frac{1}{Y}\right).$$

∴ From (9)—

$$U = \frac{X + M''Y}{M''(Y - 1)} = \frac{Y\,[M'(X + M''Y) + M''(X + M'Y)]}{M''(X + M'Y)}$$

$$U = 2Y\left[1 + \frac{(M' - M'')X}{2M''(X + M'Y)}\right]$$

$$u = 2y\left[1 + \frac{(m' - m'')x}{2m''(x + m'y)}\right] \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (20)$$

SECTION 14.

When $M' = M''$ (19) becomes—

$$Z = 2X$$
$$z = 2x \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (21)$$

(20) becomes—

$$U = 2Y$$
$$u = 2y \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (22)$$

Hence we have a complete solution in the particular case where $M' = M''$ of the dimensions corresponding to any given ratio of the losses.

Since $M' - M''$ is usually small, the solution obtained by putting $M = \frac{M' + M''}{2}$ for both M' and M'' throughout will give an approximate solution of the general case, equations (17), (19), (20) enabling us to examine the degree of approximation.

SECTION 15.

A complete algebraic solution is also found, in the particular case, for the problems of Section 7.

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Taking the problem of finding the most efficient transformer, and putting $m' = m'' = m$, we may write down the total losses—

$$Q \equiv g_i . y . u . (x + z + m y) + g_c . x . z . \left(y + u + \frac{x}{m}\right) \quad . \quad . \quad (23)$$

From (6)—

$$4 R^2 \equiv x . y . z . u - 4 F^4 = 0,$$

using (21), (22).

$$Q \equiv 2 g_i y^2 (3 x + m y) + 2 g_c x^2 \left(3 y + \frac{x}{m}\right) \quad . \quad . \quad . \quad (24)$$

$$R^2 \equiv x^2 y^2 - F^4 = 0.$$
$$R \equiv x y - F^2 = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (25)$$

The condition that Q is a minimum subject to R = 0 is—

$$\frac{d Q}{d x} \frac{d R}{d y} - \frac{d Q}{d y} \frac{d R}{d x} = 0,$$

or—

$$x \left(6 g_i y^2 + 12 g_c x y + 6 g_c \frac{x^2}{m}\right) - y (6 g_i m y^2 + 12 g_i x y + 6 g_c x^2) = 0.$$

After some reduction—

$$6 (x + m y) \left(g_c \frac{x^2}{m} - g_i y^2\right) = 0,$$

rejecting the solution $x + m y = 0$—

$$\frac{x^2}{y^2} = \frac{m g_i}{g_c} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (26)$$

whence by (24)—

$$Q \equiv 2 g_i y^2 \{(3 x + m y) + (3 m y + x)\},$$

and the ratio of iron and copper losses is—

$$\frac{3 x + m y}{3 m y + x}$$

a quantity whose upper and lower limits are 3 and $\frac{1}{3}$.

By (25) and (26)—

$$\frac{x^4}{F^4} = \frac{m g_i}{g_c},$$

rejecting all negative roots—

$$\left.\begin{aligned} x &= \sqrt[4]{\frac{m g_i}{g_c}}\, F \\ y &= \sqrt[4]{\frac{g_c}{m g_i}}\, F \\ z &= 2 x \\ w &= 2 z \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (27)$$

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Section 16.

If k_i, k_c be substituted for g_i, g_c in (27), we get the dimensions of the cheapest transformer as far as cost of active materials goes.

It is seen at once that the two solutions are the same only if $\frac{k_i}{k_c} = \frac{g_i}{g_c}$, and not otherwise.

This solution is evidently an approximate solution of the general case when $M' - M''$ is small.

Section 17.

It has hitherto been supposed that both copper and iron densities are rated up as high as possible, leaving a reasonable margin of safety.

Under these circumstances the assumption is justified that the flux and current densities are constant for a pretty wide range of dimensions.

In British practice another case arises where a large amount of material is put into a transformer at low densities to keep down the no-load losses without sacrificing regulation.

If we replace d_i and d_c by two variables μ and ν, we may vary μ and ν subject to the condition $\mu \times \nu =$ constant, without altering the output.

Again, if—

$$w_i = a\mu^n \ (n = 1{\cdot}5 \text{ to } 2),$$
$$w_c = \beta\nu^2.$$

we may increase the efficiency by increasing all the linear dimensions in the same proportion.

It has already been established that for any values of μ and ν we can find unique values of the dimensions which give minimum losses in any arbitrary ratio.

Combining these two methods, it is clear that by varying the densities and dimensions we can obtain any values for the iron and copper losses for any ratio of μ and ν.

The new problem is, what ratio of μ and ν gives the cheapest transformer while meeting the specified losses.

The solution leads to abnormally low flux densities.

The analysis is beyond the scope of the present paper.

Section 18.

Example.

(50 Kilovolt-amperes Transformer, 2000/200 Volts.)

$P_0 = 50{\cdot}5.$

$d_i = 1.$ $\quad w_i = 2{\cdot}2.$

$d_c = 1.$ $\quad w_c = 2{\cdot}2.$

$f_i = 0{\cdot}9.$

$f_c = 0{\cdot}4.$

$N = 50.$

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$$F^4 = \frac{50{\cdot}5}{4 \times 11 \times 0{\cdot}9 \times 0{\cdot}4 \times 1 \times 1} = 3{\cdot}19.$$

$$F = 1{\cdot}337.$$

$$g_t = 2 \times 7{\cdot}7 \times 0{\cdot}9 \times 2{\cdot}2 = 30{\cdot}5.$$

$$g_c = 2 \times 8{\cdot}9 \times 0{\cdot}4 \times 2{\cdot}2 = 15{\cdot}7.$$

$$m' = 1{\cdot}57. \qquad m'' = 1{\cdot}27. \qquad m = 1{\cdot}42.$$

Approximate solution—

$$\begin{cases} x_1 = \sqrt[4]{\dfrac{1{\cdot}42 \times 30{\cdot}5}{15{\cdot}7}} \times 1{\cdot}337 = 1{\cdot}72. \\ z_1 = 3{\cdot}44. \\ y_1 = \sqrt[4]{\dfrac{15{\cdot}7}{1{\cdot}42 \times 30{\cdot}5}} \times 1{\cdot}337 = 1{\cdot}035. \\ u_1 = 2{\cdot}07. \end{cases}$$

The losses calculated on the supposition that $m' = m''$ are by (26)—

$$2\,g_t\,y_1^2\,(3\,x_1 + m\,y_1) \quad \text{and} \quad 2\,g_t\,y_1^2\,(3\,m\,y_1 + x_1).$$

Iron loss $= 2 \times 30{\cdot}5 \times 1{\cdot}035^2 \times 6{\cdot}63 = 430$ watts.
Copper loss $= 2 \times 30{\cdot}5 \times 1{\cdot}035^2 \times 6{\cdot}12 = 400$ watts.

The actual losses for the above values of $x\,y\,z\,u$ are—

$$\text{Iron loss} = 2\,g_t\,y_1^2\,(3\,x_1 + m'\,y_1) = 440 \text{ watts.}$$

$$\text{Copper loss} = 2\,g_c\,x_1^2\left(3\,y_1 + \frac{x_1}{m''}\right) = 415 \text{ watts.}$$

The ratio of actual losses is $\dfrac{3\,x_1 + m'\,y_1}{3\,m\,y_1 + \dfrac{m}{m''}\,x_1}$, which here $= 0{\cdot}95$, and, in general, is not necessarily unity.

We may test the degree of approximation by means of (19) and (20). A second approximation is—

$$z = 2\,x\left[1 + \frac{0{\cdot}3 \times 1{\cdot}04}{2\,(3{\cdot}03)}\right].$$

$$= 2\,x\,[1 + 0{\cdot}052].$$

$$u = 2\,y\left[1 + \frac{0{\cdot}3 \times 1{\cdot}72}{2 \times 1{\cdot}27 \times 3{\cdot}35}\right].$$

$$= 2\,y\,[1 + 0{\cdot}061].$$

Hence the dimensions are within 5 or 6 per cent. of the theoretically best design, and as we are in the neighbourhood of a turning value the total losses will not be out by more than a small quantity of the order of $(0{\cdot}05)^2$ or $(0{\cdot}06)^2$—that is, $\frac{1}{4}$ or $\frac{1}{3}$ per cent.

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SECTION 19.

Example of Graphical Method and Use of the Table.

$P_o = 40{\cdot}5.$

$N = 50.$

$f_i : f_c = 1 : 2{\cdot}5$

$f_i = 0{\cdot}9.$

$f_c = 0{\cdot}35.$

$d_i = 1. \qquad w_i = 2. \qquad g_i = 27{\cdot}6.$

$d_c = 1. \qquad w_c = 2{\cdot}22. \qquad g_c = 13{\cdot}8.$

$$c^4 = \frac{4}{\pi} \times \frac{40{\cdot}5}{11 \times 0{\cdot}9 \times 0{\cdot}35 \times 1 \times 1} \times \frac{50}{50} = 15.$$

$$a = \frac{2 \times 7{\cdot}7 \times 2}{110 \times 0{\cdot}35 \times f_i} = \frac{0{\cdot}8}{f_i}.$$

$$b = \frac{2 \times 8{\cdot}9 \times 2{\cdot}22}{110 \times 0{\cdot}9 \times f_c} = \frac{0{\cdot}4}{f_c}.$$

$$\frac{a}{b} = \frac{0{\cdot}8}{0{\cdot}4} \times \frac{f_c}{f_i} = 5.$$

$m' = 1{\cdot}57. \qquad m'' = 1{\cdot}27. \qquad m = 1{\cdot}42.$

$$M = m \div \frac{a}{b} = 0{\cdot}284.$$

$$\sqrt{M} = 0{\cdot}533.$$

Approximate Solution.

Drawing the line pair—

$$\left(X - \frac{1}{2}\right) = \pm \sqrt{M}\left(Y - \frac{1}{2}\right),$$

and laying off P M = K N as in Fig. 4, we get—

$$X = 1{\cdot}7, \qquad Y = 2{\cdot}7.$$

Or, using the table and reading from the bottom, by proportional parts—

$$\frac{1}{M} = 3{\cdot}52, \qquad Y = 2{\cdot}65, \qquad X = 1{\cdot}71.$$

Substituting these values of X Y and M in (13), (14), or (15) we get—

$$L^2 = 23{\cdot}5 = \frac{a}{b}\frac{c^4}{a^4}.$$

Whence in succession—

$$a^4 = \frac{5 \times 15}{23{\cdot}5} = 3{\cdot}2.$$

$$a = 1{\cdot}34.$$

$$b = \frac{a}{5} = 0{\cdot}268.$$

$$f_i = \frac{0{\cdot}8}{a} = 0{\cdot}6 \text{ per cent.}$$

$$f_c = \frac{0{\cdot}4}{b} = 1{\cdot}5 \text{ per cent.}$$

Iron loss = 242 watts.

Copper loss = 610 watts.

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Again—

$$x = a\,\mathrm{X} = 1{\cdot}34 \times 1{\cdot}7 = 2{\cdot}28.$$
$$y = b\,\mathrm{Y} = 0{\cdot}268 \times 2{\cdot}7 = 0{\cdot}725.$$
$$z = 2x = 4{\cdot}56.$$
$$u = 2y = 1{\cdot}45.$$

Substituting these values in the right-hand side of (1) and (2)—

$$\text{Iron loss} = 2 \times 27{\cdot}6 \times 0{\cdot}725^2 \times 7{\cdot}98 = 230.$$
$$\text{Copper loss} = 2 \times 13{\cdot}8 \times 2{\cdot}28^2 \times 3{\cdot}97 = 570.$$

There is a discrepancy of 5 or 6 per cent. between the two evaluations of the losses.

The ratio required, however, is accurately enough attained.

Section 20.

I am specially indebted to Dr. L. N. G. Filon, to whom I owe the method of Sections 9 and 10, and the elegant graphical solution of paragraph 11; and my thanks are due to Professor Kapp, without whose encouragement the work would at one time have been laid aside.

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JOURNAL

OF THE

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Founded 1871. *Incorporated* 1883.

VOL. 43. 1909. NO. 197.

Proceedings of the Four Hundred and Ninety-first Ordinary General Meeting of the Institution of Electrical Engineers, held in the Rooms of the Institution of Civil Engineers, Great George Street, Westminster, on Thursday evening, March 25, 1909—Mr. W. M. MORDEY, President, in the chair.

The minutes of the Ordinary General Meeting, held on March 11, 1909, were taken as read, and confirmed.

Messrs. H. L. Dixon and F. L. Moysey were appointed scrutineers of the ballot for the election of new members, and, at the end of the meeting, the following were declared to have been duly elected :—

ELECTIONS.

As Member.

David Alfred Starr.

As Associate Members.

George Dania.
Gerald Maxfield Maddock.
George Edmund Marley.
Nathaniel David B. Phillips.
Archibald Hugh Smyth.
Frank Harold Wardle.
Arthur Cecil Wright.

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As Students.

George John Baldock.
Henry Percy Clinch.
Peter James Cottle.
Richard Dawson Fairclough.
William Horace Grint.
Bruce Hamer Leeson.
Arthur Haydock Ogden.
Harold P. Pentelow.
Edward Arthur Richards.

Donations to the *Library* were announced as having been received since the last meeting from L. A. Bauer, E. Kolben, D. Korda, the Liverpool Corporation Tramways, A. Righi, L. H. Walter; to the *Building Fund* from A. Hay; and to the *Benevolent Fund* from G. Allom, Major P. Cardew, M. S. Chambers, R. A. Chattock, W. C. Clinton, P. R. Cobb, V. K. Cornish, B. Davies, J. L. Devonshire, H. C. Donovan, B. M. Drake, C. V. Drysdale, K. Edgcumbe, E. Fawssett, E. Garcke, Dr. R. T. Glazebrook, F.R.S., F. E. Gripper, H. G. Harris, Colonel H. S. Hassard, C. C. Hawkins, J. S. Highfield, H. A. Irvine, E. S. Jacob, Dr. G. Kapp, A. E. Levin, E. Manville, A. E. Mead, L. B. Miller, W. M. Mordey, Major W. A. J. O'Meara, C.M.G., Hon. C. A. Parsons, C.B., F.R.S., W. H. Patchell, A. H. Preece, L. Preece, Sir W. H. Preece, K.C.B., F.R.S., T. Rich, R. Robertson, S. R. Roget, W. H. Scott, G. H. Sayers, A. Siemens, J. F. C. Snell, A. Stroh, A. J. Stubbs, A. P. Trotter, H. L. W. Ward, and R. P. Wilson, to whom the thanks of the meeting were duly accorded.

The PRESIDENT: I hoped to have had the pleasure of calling on Mr. Rider to read his paper on the Electrical System of the London County Council Tramways. Unfortunately Mr. Rider is ill, but his assistant, Mr. Shepherd, will read the paper in his absence.

A paper (see page 235) by Mr. John H. Rider, entitled "The Electrical System of the London County Council Tramways," was read and discussed.

The meeting adjourned at 9.40 p.m.

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THE ELECTRICAL SYSTEM OF THE LONDON COUNTY COUNCIL TRAMWAYS.

By JOHN HALL RIDER, Member.

(*Paper received February 2, read in London on March 25, and at Dublin on April 8, 1909.*)

INTRODUCTION.

What is now known as the London County Council Tramways consists of what was formerly a number of independent tramway undertakings within the County of London, together with certain new lines built by the Council itself. The former were constructed as horse lines, and portions of them are still so worked, while the latter were constructed as electric lines, the large majority being on the conduit system.

The Council has, up to the present, purchased the tramways mentioned in Table I., page 236.

By the London County Tramways Act, 1896, the Council was empowered to work the London Street Tramways (which it had then purchased), and any other tramways within the County of London, "as and when such tramways are acquired by the Council." In that year, however, the London Street Tramways and the North Metropolitan Tramways were leased to the North Metropolitan Company for fourteen years, and it was not until 1898, when the Council decided to purchase the London Tramways undertaking on the south side of the Thames, that active steps were taken to put the powers of the 1896 Act into operation. The actual transfer of these lines took place at midnight on December 31, 1898, and on that date the "London County Council Tramways" came into existence.

In February, 1899, Dr. (now Sir) Alexander Kennedy was asked to report "(*a*) as to the best system or systems of mechanical traction, other than steam or cable, for adoption on the tramways; (*b*) where, or under what conditions, an experimental line could best be introduced to initiate such system or systems, and (*c*) generally on the whole subject."

Dr. Kennedy's report was dated June 5, 1899, and recommended the use of the centre-slot conduit system for an experimental line of 5 or 6 miles of route. The report was adopted by the Council, and Dr. Kennedy was appointed to design and carry out the work of electrifying, as an experiment, what are now known as the Westminster, Waterloo, Blackfriars, and Tooting routes.

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The electrification of these specific routes (among others) was authorised by the London County Tramways Act, 1900, and the London County Tramways (Electrical Powers) Act, 1900, gave the Council

TABLE I.

Name of Undertaking.	Date of Purchase.	Length (Street-miles).	Cost of Acquisition.	Remarks.
			£	
London Street Tramways (part of)—permanent way and buildings ...	1895	4¼	225,572	Originally leased to North Metropolitan Tramways Company from June, 1896, until June, 1910. Lease surrendered March 31, 1906, and lines since worked by the Council.
London Street (remainder) and North Metropolitan Tramways — permanent way and buildings	1896	43½	580,307	
Northern Tramways—cars, plant, etc.*	1906	—	223,691	
London Tramways ...	1899	24⅜	882,043	Worked by Council.
South-Eastern Metropolitan Tramways	1902	2½	50,166	
South London Tramways	1902	13¼	232,178	
London, Deptford, and Greenwich Tramways ...	1904	6⅞	96,327	
London, Camberwell, and Dulwich Tramways	1904	2⅞	6,544	Abandoned and taken up in 1906.
Woolwich and South-East London Tramways	1905	4¾	49,930	Narrow gauge lines worked by Council.
London Southern Tramways ...	1906	5¾	62,085	Worked by Council.
Totals		105¼	2,408,843	

* Purchased from North Metropolitan Tramways Company by special arrangement, in addition to which £97,787 was paid as compensation for the surrender of the Company's lease.

powers to adopt and use electric traction on "any tramway in the administrative County of London which has been, or shall be, acquired by the Council, or which shall be constructed by the Council under the

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powers of any Act of the present session." The same Act also provided (Clause 23) that the overhead system should not be used in any parish or district without the consent of the "vestry of such parish or the board of works for such district."

The London County Tramways Act, 1900, gave powers to the Council to use the site of its Camberwell depôt for a generating station, and the sites of four other depôts for sub stations. In a later Act (1906) a general power was obtained to use "any lands now belonging to or hereafter acquired or appropriated by them" for sub-stations.

The author does not propose to refer in detail to the reconstruction of the "experimental" or Tooting line under Sir A. Kennedy's supervision, as this was fully described in a paper read by Mr. Millar before the Institution of Civil Engineers in 1904.* Neither does he deal, in this paper, with the track work, conduit construction, cars, or car-sheds of the system generally, except so far as they affect the electrical generating, transmitting, transforming, and distributing systems for which he is responsible.

When the author was appointed in February, 1901, he found the plans for the Camberwell Generating Station well advanced, and tenders let for the first set of boilers. The intention at that time was to work the whole of the tramways south of the Thames from this station, and to build another station on the north of the Thames when the lines then leased to and worked by the North Metropolitan Tramways Company should revert to the Council in 1910. Low-tension direct-current generators, working at from 500 to 625 volts, were to be used for the lines in the vicinity of the Camberwell station, and high-tension 3-phase generators, working at 6,600 volts, with local sub-stations, for the outlying districts. The complete designs provided for about 20,000 k.w.

A brief study of the situation showed that, except for its central situation with regard to the southern lines, the Camberwell site had nothing to recommend it, but had, on the contrary, most serious disadvantages. The whole of the coal (some 150,000 tons per annum) would have to be brought by rail, and the ashes removed by the same means. Taking the difference in freight between rail borne and water borne coal as 3s. per ton, the extra carriage alone would be £22,500 per annum over a river site. As there was no supply of water, either non-condensing engines would have to be used or cooling towers employed. Either of these alternatives would undoubtedly have proved a most serious nuisance to the neighbourhood.

The author, therefore, determined to look out for a more suitable site, with the view of advising the Council to abandon the one at Camberwell, and was fortunately able to find one already in the possession of the Council as a horse depôt at Greenwich.

In July, 1901, the Council agreed to the use of the Greenwich site in lieu of Camberwell, and the author's designs were adopted shortly

* *Proceedings of the Institution of Civil Engineers*, vol. 156, p. 143, 1904.

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afterwards for the lay-out and equipment. Parliamentary powers were obtained in the Council's Tramways and Improvements Act, 1902.

As it was realised that the change of site from Camberwell to Greenwich would cause delay in the supply of energy, arrangements were made with the South London Electric Supply Corporation, Ltd., for the erection, on their land at Loughborough Junction, S.E., of a temporary building, in which the Council placed two Ferranti-Dick-Kerr, 1,500-k.w. direct-current steam generators. These were supplied with steam by the South London Company, and were operated by the Council's staff. The supply began with the opening of the Tooting lines in May, 1903, and continued until July 19, 1906, when the load was taken over by the Greenwich station.

At a later date two similar 1,500-k.w. 3-phase sets were erected in the Deptford station of the London Electric Supply Corporation, Ltd., and were used for supplying the Greenwich and Peckham routes. On the termination of the agreement the plant was purchased by the Corporation, who also bought the Ferranti engines at Loughborough Junction.

The electrification of other lines before the opening of the Greenwich station rendered it necessary to obtain other temporary supplies of power, and for some time energy was taken from the Bankside station of the City of London Electric Lighting Company, Ltd., and from the City Road station of the County of London Electric Light Company, Ltd. Pending the completion of the Holborn sub-station, a supply was also taken for a short time from the Charing Cross sub-station of the Underground Electric Railways Company. At the present time a supply is still taken from the Deptford station of the London Company.

The author wishes to place on record his keen appreciation of the help given him by the engineers of the various companies from whom the Council has purchased energy at various times. He would particularly thank Mr. Bailey of the City Company, Mr. Partridge of the London Company, and Mr. Sparks of the County Company, for many personal kindnesses and favours.

Since 1900 the Council has obtained powers for the construction of various new tramways in extension of, and for linking up, its existing system. Many of these have been built, while others have been held up for various reasons. At March 31, 1908, the total length of the Council's tramways, both north and south of the Thames, was approximately as follows:—

Electric Traction—

Worked by the Council	...	68¼ street-miles.
Worked by the M.E.T....	...	⅜ ,,
Horse Traction	...	51¾ ,,
Total		120-⅜ street-miles.

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The portion worked by the Metropolitan Electric Tramways, Ltd., is the short length in Archway Road, Highgate, which connects with the tramways of the Middlesex County Council.

The accompanying map (Fig. 1) shows the complete system together with the positions of the generating and sub-stations.

Greenwich Generating Station.

The Greenwich Generating Station is situated on the River Thames, and, as its position has been the cause of a great deal of discussion, it may be well to define it particularly.

It is in latitude 51° 29′ 2″ North, and longitude 0° 0′ 0″, while the level of the engine-room floor is 21·88 ft. above ordnance datum. The site covers an area of approximately 3¾ acres, and has a frontage to the river of 240 ft., to Hoskins Street of 648 ft., and to Old Woolwich Road of 308 ft.

The general lay-out of the station may be seen from Fig. 2. It consists of a boiler house 445 ft. long × 80 ft. wide, an engine-room of the same dimensions, and auxiliary buildings adjoining. The buildings were designed by Mr. W. E. Riley, F.R.I.B.A., the Council's architect, to the requirements of the author, and the external elevation has been treated broadly, having in view the scale of the building and the object for which it is constructed. The foundation is a concrete raft 6 ft. thick, extending over the whole of the site, with concrete retaining walls. The superstructure is a steel framework enclosed externally with brick walls having Portland stone dressings.

The whole of the boiler- and engine-rooms are faced inside with ivory-white glazed bricks, with a brown glazed dado, and the roofs consist of steel principals, which support a covering of coke breeze concrete, the exterior being slated. The floors throughout are of concrete, and are covered either with granolithic or terrazzo paving.

The four chimney shafts have each an internal diameter of 14 ft., the first two being at a height of 250 ft., and the last two of 182 ft., in both cases measured above the firing floor. The two latter chimneys were not carried above 182 ft., in consequence of the agreement with the Admiralty, in connection with the Greenwich Observatory.

Coaling Arrangements.—A large pier has been constructed which projects into the river Thames for a distance of about 118 ft. in front of the river wall. As will be seen from Fig. 2, the pier is T-shaped in plan, and has a river frontage of 200 ft., with a width of 40 ft. 6 in. It was built to the designs and under the supervision of Mr. M. FitzMaurice, C.M.G., the Council's chief engineer.

The pier rests upon 16 cast-iron cylinders sunk in the bed of the river to a depth of about 26 ft. below ordnance datum, or about 18 ft. below the bed of the river. The cylinders were filled with concrete, and support a framework of steel girders on which a timber

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platform is placed. The top of the pier is 34 ft. 6 in. above Trinity high-water level, or about 70 ft. above the bottom of the cast-iron cylinders. The pier was constructed at this height in order that the coaling trucks might be run directly over the outside coal bunkers which join the pier on the wharf side.

The outside coal bunkers are built of steel, and have a capacity of about 2,000 tons. They are covered by a roof, and the lower portion of the bunkers is immediately over the coal and ash conveyors, mentioned later. Colliers up to 2,000 tons can be accommodated in front of the pier, and are unloaded by three electric jib cranes having Priestman's grabs, each of a capacity of 1 ton. These cranes run on a track of 8-ft. gauge along the front of the pier, and discharge the coal directly into steel wagons, each of which has a capacity of 5 tons.

The coaling cranes have fixed jibs with a reach of 35 ft. from the centre of the crane, which is sufficient to reach any part of the holds of the steamers. Each crane has two direct-current, 550-volt series motors, one of 50 H.P. for lifting, and one of 10 H.P. for slewing and travelling. Only one of the latter operations can be carried out at once. When the cranes have been brought to their correct positions for unloading, their trucks are clamped to the track rails.

The supply of current is brought to the cranes by means of flexible cables from protected plug boxes on the pier.

Tracks to the standard gauge of 4 ft. 8½ in. are laid on the pier and the coaling wagons are hauled by electric locomotives, the current being supplied through a third rail at 550 volts pressure. The locomotives consist of ordinary four-wheeled tramway trucks, with the usual motor and controller equipment, and a light steel house for the protection of the driver. Both locomotives and wagons are fitted with automatic couplers for use in shunting.

Each of the coal-wagons is adjusted to the same tare by lead weights in pockets, and the weigh-bridges over which the trucks pass before discharging their coal into the outside bunkers are arranged with false zeros, so that only the net weight of coal is measured.

The weigh-bridges indicate upon large dials, about 5 ft. in diameter, and accurate readings to within about 3 lbs. on a load of 5 tons can be obtained. Each wagon is weighed as it passes over the weigh-bridge, and the weights so obtained are accepted by the coal merchants, and on them the accounts for the coal are passed.

The capacity of the coal unloading system is about 2,000 tons per day of 24 hours, using only two out of three cranes. This is ample for the requirements of the station.

The coal used at present is North Country washed singles, and is brought by steamers directly from Grangemouth on the Forth. The coal is bought annually by contract, and is paid for according to its quality. It may be interesting here to give briefly the conditions under which the coal is purchased.

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C TRAMWAYS. 1908-9.

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THER ELECTRIC LINES. ——
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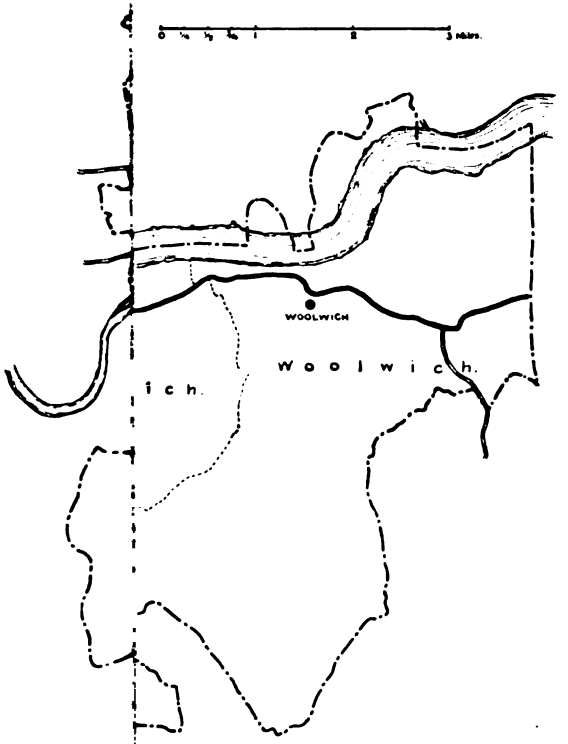

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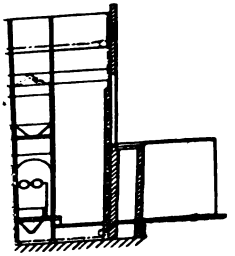

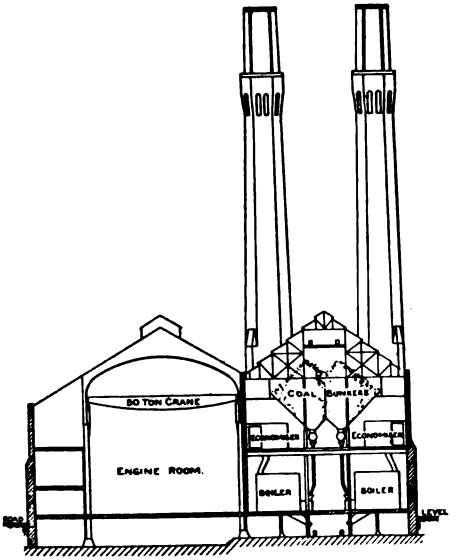

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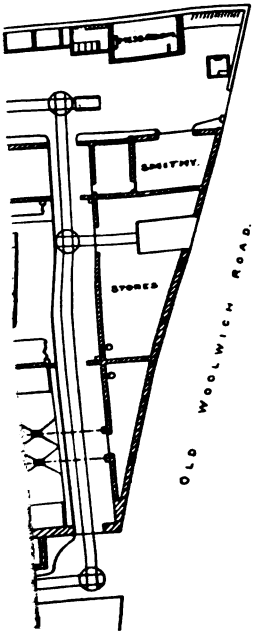

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The specified standards are :—

Calorific value	12,500 B.Th.U. per lb.
Small (as measured by the quantity which will pass through a wire sieve of $\frac{3}{8}$ in. square mesh) ...	20 per cent. by measurement.
Moisture	10 per cent. by weight.

The calorific value and moisture are measured by the Council's chemist on samples taken from every 100 tons brought over the pier front. The calorific value is determined by a Mahler bomb calorimeter on a sample previously dried at 100° C., and the amount of moisture is determined on a weighed portion of the sample, as taken from an air-tight sample tin.

The proportion of small coal is ascertained on the pier on a sample of about 50 lbs. in weight, taken, at the option of the Council, either from the hold or from the quantity unloaded by the grabs.

If the quality of the coal in any cargo, as ascertained by samples tested, be found different as regards calorific value, moisture or small, from the above standards, the price paid to the contractor is varied as follows :—

(*a*) If the calorific value exceed 12,500 British thermal units per pound, the price per ton is increased in the same percentage ratio as the increase in the calorific value.

(*b*) If the calorific value be less than 12,500 British thermal units per pound, the price per ton is decreased in the same percentage ratio as the decrease in the calorific value. The Council, however, has the right to reject the whole cargo if the calorific value be less than 10,500 British thermal units per pound.

(*c*) If the moisture be less than 10 per cent. by weight, the weight of coal to be paid for is increased beyond the quantity actually weighed out by a percentage equal to the percentage decrease of moisture.

(*d*) If the moisture exceed 10 per cent. by weight, the weight of coal to be paid for is decreased below the quantity actually weighed out by a percentage equal to the percentage increase of moisture. The Council, however, has the right to reject the whole cargo if the moisture exceed 13 per cent. by weight.

(*e*) If the proportion of small coal be less than 20 per cent. by weight, the weight of coal to be paid for is increased beyond the quantity actually weighed out by a percentage equal to one-quarter of the percentage decrease of small coal.

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(*f* If the proportion of small coal exceed 20 per cent. by weight the weight of coal to be paid for is decreased below the quantity actually weighed out by a percentage equal to one-quarter of the percentage increase of small coal. The Council, however, has the right to reject the whole cargo if the proportion of small coal exceed 25 per cent. by weight.

These conditions have worked exceedingly well in practice. The coal merchants were a little chary at first at accepting a contract with such conditions, but, after a little experience, they found that they were easily able to meet them, and the result has been that an increased price is paid for practically every cargo of coal because it is better than the standard. This is a gain to the Council in every way, as not only is the quality and size of the coal very uniform, but, being so, its handling and burning become an easy matter.

The object of using an outside coal bunker of so large a capacity as 2,000 tons was to enable a steamer to be discharged in the shortest possible time, without depending upon the comparatively slow rate of travel of an ordinary conveyor. When a steamer has to bring coal from either Wales or the Northern ports the time taken to discharge her is often as long as the voyage between the port of loading and the port of discharge. It is, therefore, of the utmost importance that the unloading should be quickly done in order that the best use may be made of the vessel.

The outside coal bunkers have sloping bottoms, which terminate in mouth-pieces with hand-operated valves. The mouth-pieces discharge the coal through automatic fillers into the gravity bucket conveyors beneath. Fig. 3 is from a photograph of the conveyor-room immediately under the outside coal bunkers.

There are two lines of coal conveyors, each of which has a capacity of 40 tons per hour. After leaving the outside bunkers the conveyors rise within the boiler house to the top of the main coal bunkers, which are situated over the boilers.

On their return journey the conveyors pass through the ash tunnel in the basement of the boiler house, and carry the ash from the ash hoppers under the boilers to a large storage hopper under the pier, whence it is discharged into barges which can lie alongside the river wall without interfering with the coaling steamers. Fig. 2 shows the route of the coal and ash conveyors.

Each line of conveyors is driven by a 25-B.H.P. 3-phase motor, with squirrel-cage rotor, working at 475 revs. per minute, and supplied with 3-phase currents at 220 volts between phases. These motors are started by an ordinary 3-pole switch without any special devices, and the circuit breakers controlling them may be tripped from a number of points in the station by means of safety pushes.

The driving gear is fixed at the top of the first vertical rise in the boiler house, and, to prevent the conveyor from running backwards when the motor stops, owing to the excess weight of the coal in the

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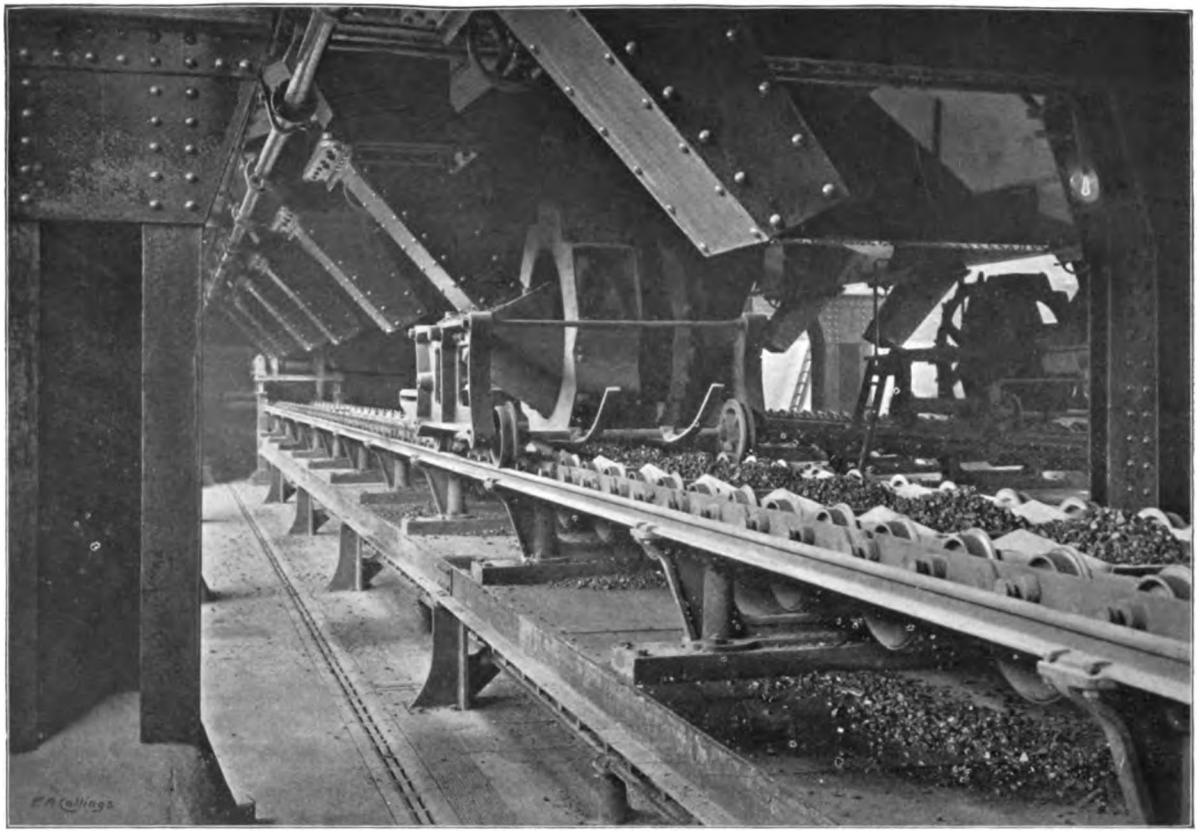

FIG. 3.—Greenwich Generating Station—Conveyors under Coal Bunkers.

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vertical limb, a pawl is arranged to engage between the links of the conveyor chains. This pawl would also prevent the chain from falling should the chain break from any cause.

At the south end of the boiler house, where the conveyor chains descend empty, an ingenious arrangement has been provided to prevent the chains and buckets from falling in the event of breakage. Two continuous vertical runners have been fixed the whole height of the building, and, should the chain break, it can only fall for a distance of a few inches, as it would quickly jam in the runners, as will be seen by Fig 4. This device was designed by Messrs. Spencer & Co., Ltd., of Melksham, who carried out the extensions to the conveyor system. The conveyors for the first portion of the station were made by the New Conveyor Company, Ltd.

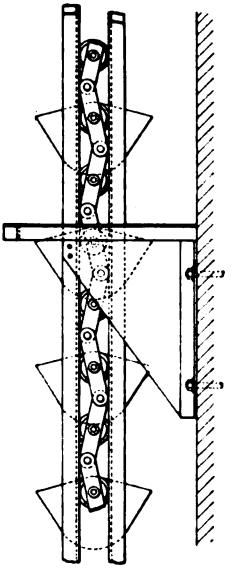

FIG. 4.—Greenwich Generating Station—Conveyor Safety Device.

Fillers of the same type as those used for the coal are employed for the ashes in the ash tunnel.

The main coal bunkers are situated at the top of the boiler house, immediately over the economisers, which are described later. The bunkers are built of steel and concrete, and are subdivided into as many separate compartments as there are boilers. Each bunker will hold about 200 tons of coal, or roughly, 9,600 tons for the whole of the 48 bunker compartments.

Wrought-iron pipes, 3 in. diameter, are fixed in each bunker, right to the bottom of the coal, and can be reached at the top from the accommodation gangways. Thermometers can be lowered at any time through these pipes, and the temperature of the coal at the bottom of the bunker ascertained. So far nothing above the normal temperature has been registered, but, in the event of the coal showing any tendency to heat after long storage, it would be quickly discovered. A series of water jets are arranged over the bunkers, which can be operated from below in case of fire.

The coal falls by gravity from the bunkers through measuring boxes into the hoppers of the mechanical stokers.

Boilers.—The boilers are arranged in pairs in two rows in the boiler house, 6 boilers on each side of each of the four chimneys, or 48 boilers in all in 8 groups. At the present moment only 36 boilers are in position, but the other 12 are in course of erection. The working pressure is 180 lbs. per square inch.

The first 24 boilers to be erected were of the Stirling water-tube type. Each of these boilers has an evaporative capacity of about

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16,300 lbs. of water per hour from and at 212° F., and is fitted with chain grate stokers.

The boilers are of the ordinary 5-drum pattern, made by the Stirling Boiler Company, Ltd., of Motherwell, and have proved very successful in practice. Each boiler has a superheater between the first and second banks of the vertical tubes, which forms an integral part of the boiler. By its use the steam can be superheated up to about 550° F.

The following are the results of the taking-over test on two of the boilers, after having been in operation for some six months :—

TABLE II.

Duration of test...	6 hours.
Heating surface in each boiler ...	3,320 sq. ft.
Grate area	56 sq. ft.
Class of coal used	North Country.
Calorific value of coal (determined by London County Council chemist)	11,263 B.Th.U.
Average steam pressure	180 lbs.
Average flue temperature	620·4° F.
Average feed temperature	194·3° F.
Average steam temperature	382° F.
Average superheat	130·55° F.
Average draught	from 0·5 to 0·7 in.
Total coal fired	23,674 lbs.
Total coal fired per hour	3,945·6 „
Total coal fired per boiler per hour ...	1,972·8 „
Total water evaporated (actual) ...	193,210 „
Total water evaporated per boiler per hour	16,100·8 „
Total water evaporated per hour per square foot h.s.	4·9 „
Total water evaporated per boiler per hour from and at 212° F.	18,773·53 „
Total water evaporated per hour from and at 212° F. per square foot of heating surface	5·8 „
Coal fired per hour per square foot of grate	35·2 „
Total amount of ash (wet)	3,024 „
Water evaporated per lb. of coal (actual)	8·16 „
Water evaporated per lb. of coal from and at 212° F.	9·5 „
Factor of evaporation	1·666
Efficiency	79·49 per cent.

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The remaining 24 boilers were made by Messrs. Babcock & Wilcox, Ltd. These are of somewhat larger capacity than the Stirling boilers, as they will evaporate 18,200 lbs. of water per hour from and at 210° F., and, as an overload, can evaporate 22,000 lbs. of water per hour from and at 212° F.

The Babcock boilers have each a heating surface of 4,780 sq. ft., and a grate area of 88 sq. ft., which gives a ratio of heating surface to grate area of 54·3 to 1. These boilers are fitted with chain grate stokers of the latest Babcock & Wilcox pattern, with links closer than those on the Stirling boilers, and of such a design that there are no open spaces where the links bend over the end wheels.

The general arrangement of the boilers, flues, and chimneys has proved very satisfactory in avoiding smoke. This result is, no doubt, largely helped by the excellent combustion chamber provided by the Stirling boiler, by the fact that the Babcock boilers are raised some 12 in. higher than is usual above the fire-bars, and also by the use of a large fire-brick arch immediately over the grate. There is a popular belief at the station that the smokelessness of the chimneys is accounted for by the notice, "Smoking strictly prohibited," which is prominently fixed in the boiler house on the base of one of the chimneys.

All the boilers are arranged in pairs, with convenient overhead gangways all round, giving good access to the various parts. The brickwork is glazed on the outside, whilst Glenboig fire-brick is used for the whole of the combustion chambers and arches in the furnaces. Stourbridge fire-bricks are used elsewhere for interior lining. The use of glazed bricks for the external setting is very beneficial, as it prevents a considerable quantity of air from leaking through the ordinary porous brick. This can easily be proved by feeling with the hand the outside of the glazed brickwork, which is considerably hotter than when ordinary brickwork is used.

A complete arrangement of CO_2 recorders has been fixed, each battery of six boilers having its own recorder with a separate pipe connected to the underside of the boiler up-take damper, so that any boiler may be connected at will. The usual working draught at top load is equal to about ¾ in. of water, measured between the underside of the grate and the boiler uptake, and, at half-load, about ½ in. of water. The fire thickness varies from about 4 in. to 7 in., depending upon the load and the quality of the coal. To assist the stoker draught gauges are fitted to each furnace.

Economisers.—The gases from the boilers are taken by separate steel up-takes to the floor above, where the economisers are placed. Each set of two boilers has a Green's economiser of 360 tubes, the general arrangement being in 8 groups, as shown in Fig. 2. The 8 main flues lie between the economisers and the walls of the boiler house, and afford direct short connections to the chimneys. Each flue has a large cast-iron manhole door, by which ready access is obtained for sooting, cleaning, etc.

The gases enter the economisers at between 480° and 500° F., and

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enter the chimneys at between 280° and 300° F. This temperature is just sufficient to give the necessary draught, and can be readily adjusted by means of the economiser dampers. The temperature of the feed water is raised by the economisers from between 95° and 100° F., at which it is pumped from the feed tanks, to between 230° and 250° F., at which it enters the boilers.

The scrapers of each economiser are driven by an independent 3 phase motor of 2 H.P., coupled through worm-gearing. This has been found much simpler and more convenient than the usual method of counter-shafting and belting.

Boiler Feed Arrangements.—The boiler feed pumps are situated in the basement of the boiler house under the western boilers, the two chimneys on that side dividing the basement into three separate compartments, the one between the chimneys being twice as long as the other two. Each of the smaller pump-rooms contains three pumps, and the larger pump-room contains six pumps all of the same type and make.

Each pump has three horizontal plungers, $6\frac{7}{8}$ in. diameter × 10 in. stroke, and is driven by a series-wound direct-current motor of 35 B.H.P. Each pump will deliver from 8,000 to 9,000 gallons of water per hour against a pressure of 225 lbs. per square inch when running at its full speed of 40 revs. per minute. The motors are geared to the pump shafts by worm reduction gearing having a ratio of 12 to 1.

Direct current at two different pressures—viz., 550 volts from the local sub-station and 125 volts from the auxiliary engine-room plant—is provided in the pump-room, and by means of a throw-over double-pole switch on the pump switchboards two economical running speeds corresponding to those voltages can be obtained. Intermediate speeds are obtained by resistances put into the main circuit by an ordinary type of drum controller.

The pumps were made by Mr. J. Cochrane of Glasgow, and have proved not only very efficient but very satisfactory in working. They run with very little attention, and have given practically no trouble since the works were started. The whole of the boiler supply is given by them. Tests recently taken show an efficiency between the electrical input to the motor and the water output of 60 per cent. at full load.

Each pump connects to two separate suction pipes and two separate delivery pipes, and each group of three pumps draws from two feed-water tanks, each of 5,000 gallons capacity, fixed in the basement of the boiler house on the eastern side. The feed tanks are supplied from the condensers of the reciprocating engines and turbines, and can, in emergency, be supplied directly from the town's mains through 4 storage tanks, each of 20,000 gallons capacity, situated on the roof of the boiler house annexe. The 8 feed-water tanks are connected by equalising pipes.

Make-up water is obtained from an artesian well $8\frac{1}{2}$ in. bore and

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350 ft. deep, which is situated in the condenser pump house to be described later. The water, which stands normally at a level of about 5 ft. below the top of the tube, is lifted by a vertical 3-throw motor-driven ram pump, with plungers $3\frac{1}{8}$ in. diameter by 6 in. stroke,

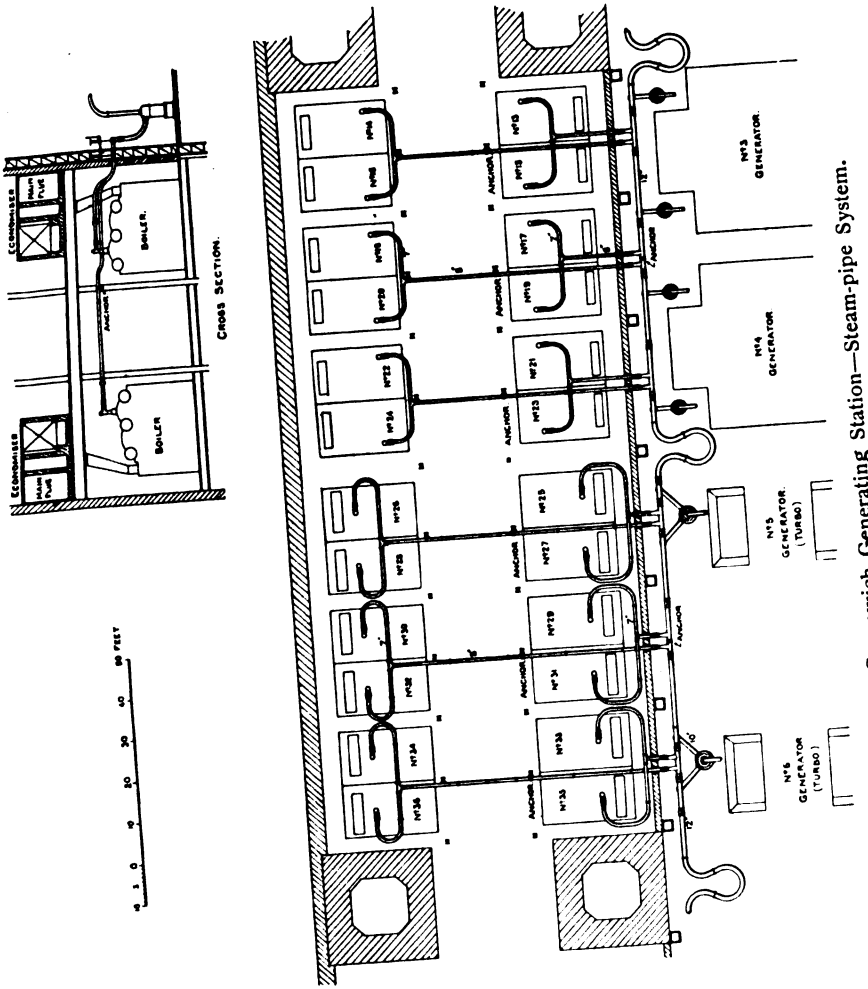

FIG. 5.—Greenwich Generating Station—Steam-pipe System.

running at 75 revs. per minute. The well will deliver about 3,000 gallons per hour, but the water, coming from the chalk, is very hard, the hardness varying between 16° and 18°; the temporary hardness being between 12° and 13°, and the permanent hardness between 4° and 5°. It has, therefore, to be treated before it can be used. For

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this purpose a Harris-Anderson water softener is used, the chemicals being lime-water and carbonate of soda. The apparatus is entirely automatic in its action, and by its means the hardness is brought down to between 7° and 8°.

The softened make-up water is stored in a tank of 48,000 gallons capacity, fixed on the roof of the condenser pump house, whence it flows by gravity to the 8 feed-water tanks in the boiler-house basement through ball valves.

No provision is made for softening town's water, should this have to be used entirely for boiler feed instead of water from the condensers. The chances of the town's supply having to be used for the whole station are so remote that it would not have paid to have put down softening apparatus for it. A connection from the town's supply is, however, taken to the water softener as an alternative to the artesian well supply for make-up water.

The water which is delivered from the condensers of the turbines is, of course, free from oil, and so is taken directly into the feed-water tanks. The water, however, which comes from the condensers of the reciprocating engines has to be treated to remove the cylinder oil, and this is done by Harris-Anderson purifiers, situated in the basement adjoining the feed tanks. The positions of these are indicated on the general plan of the station shown in Fig. 2. The chemicals used are sulphate of alumina and carbonate of soda, and all traces of oil can be absolutely removed. The alkalinity of the treated water is between 0·5° and 1°.

Each group of three pumps supplies 12 boilers through duplicate feed ranges, either direct or through the economisers, and the feed water is measured by Kennedy watermeters fixed in the pump-rooms.

Pipework.—The whole of the suction pipes between the feed tanks and the feed pumps are of cast iron, and the delivery pipes between the pumps, the economisers, and the boilers are of steel.

A portion of the steam-pipe system is shown in Fig. 5. The pipes connecting the boilers to the steam header are 8-in. bore, and are of lap-welded steel, with flanges welded on. Each pair of boilers is considered as one unit so far as the steam pipes are concerned, and they are connected, as shown in the Fig., by a 7-in. loop, from which an 8-in. pipe goes across the boiler-room directly to the 12-in. steam header in the engine-room.

The steam-pipe arrangement is very simple, and the main principles which were kept in view in its design were :—

1. That the line of the pipes should fall the whole way from the boiler stop valve to the engine separator, so that all water would travel in the same direction as the steam.
2. That the expansions and contractions due to changes of temperature should be controlled by provision of facilities for the movements of the pipes in certain directions and restrictions of the movements of others.
3. That the pipes should be as short as possible.

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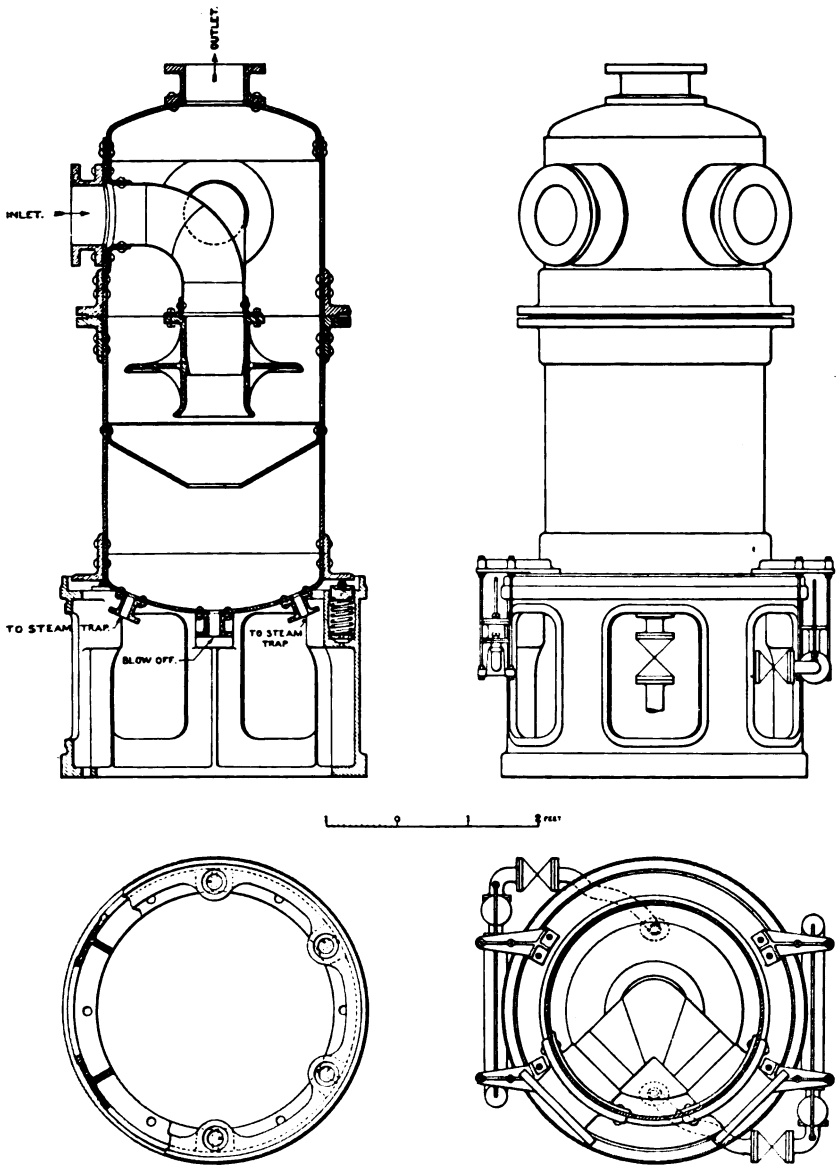

FIG. 6.—Greenwich Generating Station—Steam Separator.

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The illustration will show clearly the arrangement which has been adopted. Any water which forms in the pipes, either when the engines are working or not, falls by gravity, and is impelled by the steam to the separators in the engine-room, which are the lowest points of the system. These separators are described below.

The 10-in. branches from the steam header to the separators are taken from the underside of the header, and constitute the header water drains as well as the supply pipes to the separators.

The 8-in. pipes crossing the boiler house from the western range of boilers to the engine-room are anchored in the middle of their length to the boiler-house stanchions. The anchoring is carried out by cast-iron clamps, bolted to the brackets attached to the stanchions. Expansion in these long lengths is provided for by the loops which connect to the boiler stop valves, and by the bends which dip down and connect to the steam header. The 8-in. pipes which connect the eastern range of boilers to the header are not anchored at all, as they are comparatively short.

The main header itself is anchored in four places, two of which are indicated in the figure, so as to divide the expansion of the total length of the header into eight sections, where it can be readily dealt with by the three expansion bends provided. The expansion bends are fixed horizontally, so that there is no restriction to the passage of water along the header in either direction.

The steam pipes are generally supported in the boiler house by clamps and wrought-iron suspension rods from the ceiling, and in the engine-room by rollers on brackets built into the wall or carried on the building stanchions. The joints in the steam-pipe range are made by means of "Klingerite."

The arrangement of the steam piping has been very successful. Steam can be turned on to any engine at any time with the certainty that all the pipes up to the engine stop valves are free of water. No trouble is experienced with leaky joints due either to overstraining or to water hammer.

An interesting feature in the steam-pipe system is the design of the separators, to which reference has previously been made. This is shown in Fig. 6. The separator, which is merely a steel vessel in which the direction of the steam flow is suddenly changed, rests upon a series of steel balls, which are carried upon spring-borne supports in a cast-iron stand, which is bolted to the floor of the engine-room. The separators can thus move in any direction, either sideways by rolling on the balls, or up or down by relieving or compressing the springs. In practice it is found that they move considerably under pipe contractions and expansions, and their motion shows conclusively the kind of strains which would have come upon the pipe joints had the separators been firmly fixed to the floor.

Each separator is drained by either one or two Geipel steam traps directly to the feed-water tanks. The traps are supported by the separators and connected by curved steel pipes, having sufficient elasticity to allow of the free movements of the separators.

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The boiler stop valves are worked from gangways running along the tops of the boilers, while the valves in the boiler branches where they connect to the steam header, the section valves in the steam header, and the valves in the branches leading to the separators are all worked from a valve gallery which runs the whole length of the engine-room on the west side. The valves, which lie below the gallery, are operated by means of hand wheels, carried on cast-iron pillars, with extension rods from the valve spindles. The valve gallery is shown in Figs. 8 and 13.

The external surface of the steam-pipe system, uncovered, is about 8,000 sq. ft., or about 0·235 sq. ft. per kilowatt of total normal capacity of the station. The pipes are covered with blue asbestos and planished steel.

The atmospheric exhaust pipe runs in the basement of the engine-room, and has three vertical risers, one at the north end of the station, 3 ft. 6 in. by 3 ft. 6 in. square section, and the other two at the south end of the station, 3 ft. in diameter each. The risers are capped with exhaust heads for the purpose of catching any condensed water spray.

The whole of the atmospheric exhaust piping is of riveted steel, and the header in the basement, which is carried on rollers, varies from 27 in. to 50 in. in diameter. The highest point is in the middle of the engine-room, and the pipes fall each way to large exhaust drain boxes at the feet of the vertical risers. The boxes are drained by 6-in. pipes.

The exhaust branches from the engines and turbines are controlled by automatic atmospheric valves, which open should the condensers fail. These valves are water sealed.

The condenser water piping, the arrangement of which is described more fully later in dealing with the condenser pumping plant, is of cast iron throughout.

Generating Plant.—The engine-room contains at present four vertical-horizontal reciprocating engines, coupled to alternators of 3,500-k.w. capacity, at a power factor of 0·94, and two turbo-alternators, each of 5,000 k.w. capacity at a power factor of 0·85. Two additional turbo-alternators of the same output are also in course of erection. The total normal capacity of the station is, therefore, 34,000 k.w., but as each set is capable of dealing with an overload of 25 per cent. the station can, on emergency, be worked up to 42,500 k.w. capacity. Allowing one reciprocating and one turbine set as spares, the maximum working load may be taken at 30,000 k.w.

The 8 generating sets correspond with the 8 groups of boilers and economisers, the 8 main flues, and the 8 feeder switchgear sections.

The four reciprocating engines will probably be of interest, as they are, so far as the author is aware, the only examples of their type on this side of the Atlantic. Each engine consists of two complete half-engines, one on each side of the generator, with a vertical high-pressure cylinder, 33½ in. in diameter, and a horizontal low-pressure cylinder, 66 in.

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in diameter. The stroke is 4 ft., and the two connecting rods of each half-engine work independently on to a common overhung crank pin. The engines run at 94 revs. per minute, and the mean piston speed is 750 ft. per minute.

Fig. 7 shows a plan of one of these engines with its alternator, etc., and Fig. 8 an elevation, from which their principal characteristics will be noticed. This type of engine has many advantages in practice, particularly if the arrangement adopted at Greenwich of placing the high-pressure cylinder vertically is followed. The engines of this type made by the Allis-Chalmers Company in the United States have the high-pressure cylinder horizontal and the low-pressure cylinder vertical, with the evident intention of relieving the low-pressure cylinder of the weight of the large piston. It will be seen, however, from Fig. 9, that this arrangement introduces serious disadvantages in connection with the draining, as a large water pocket is bound to be formed in the receiver pipe, which couples the high-pressure to the low-pressure cylinder.

The Greenwich engines have a perfectly natural drainage system, as will be seen from Fig. 10, and there are no pockets where water can lodge. The low-pressure cylinder connects directly to the condenser, and the excellent facilities which the Corliss arrangement of valves affords are most effective in draining it. This feature is so marked that there is no necessity for any auxiliary cylinder drains of any kind whatever. The weight of the low-pressure piston is partly taken by a tail rod.

When the preliminary designs of the station were in preparation in 1902 the relative advantages of taking high-pressure superheated steam through heating tubes in the receiver on its way to the high-pressure cylinder, and of taking a branch from the high-pressure superheated steam supply directly through the receiver tubes were considered, and it was decided that the advantages lay with the latter arrangement, principally because of the piping difficulty of taking steam directly into the high-pressure cylinder, should either the superheat or the reheater fail for any reason. The Greenwich engines are, therefore, arranged with a reheater receiver between the high-pressure and the low-pressure cylinders, through the tubes of which live steam is taken. The reheater receivers are shown in Figs. 7 and 8, and the heating tubes have a surface of about 1,100 sq. ft.

Corliss valves are used on both the high- and low-pressure cylinders, the high-pressure admission valves being controlled directly by the governor. The low-pressure admission valves can be adjusted by hand.

The engines were designed and built entirely as enclosed engines, and work with forced oil lubrication. Oil tanks are formed under the bed of each half-engine, and duplicate oil pumps on each side, worked by the low-pressure eccentric rods, supply oil to the whole of the moving parts, including not only the main bearings, but the guides, cross heads, crank pins, eccentrics, etc.

An independent steam supply is given to each high-pressure cylinder

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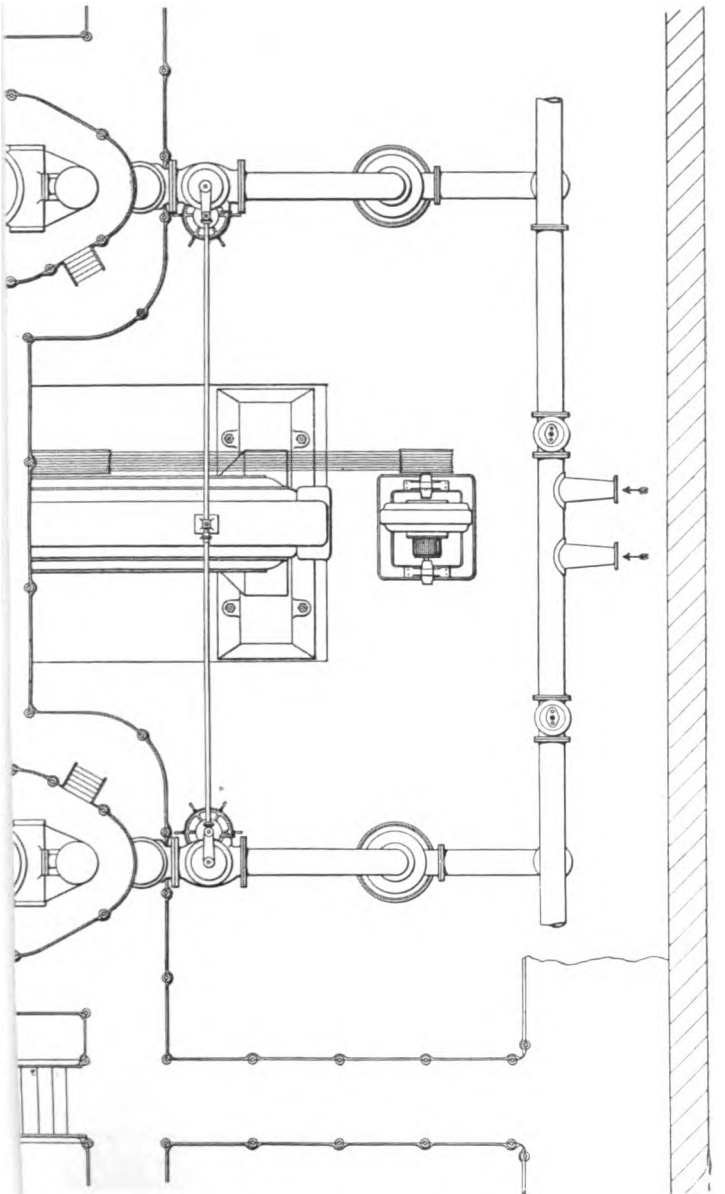

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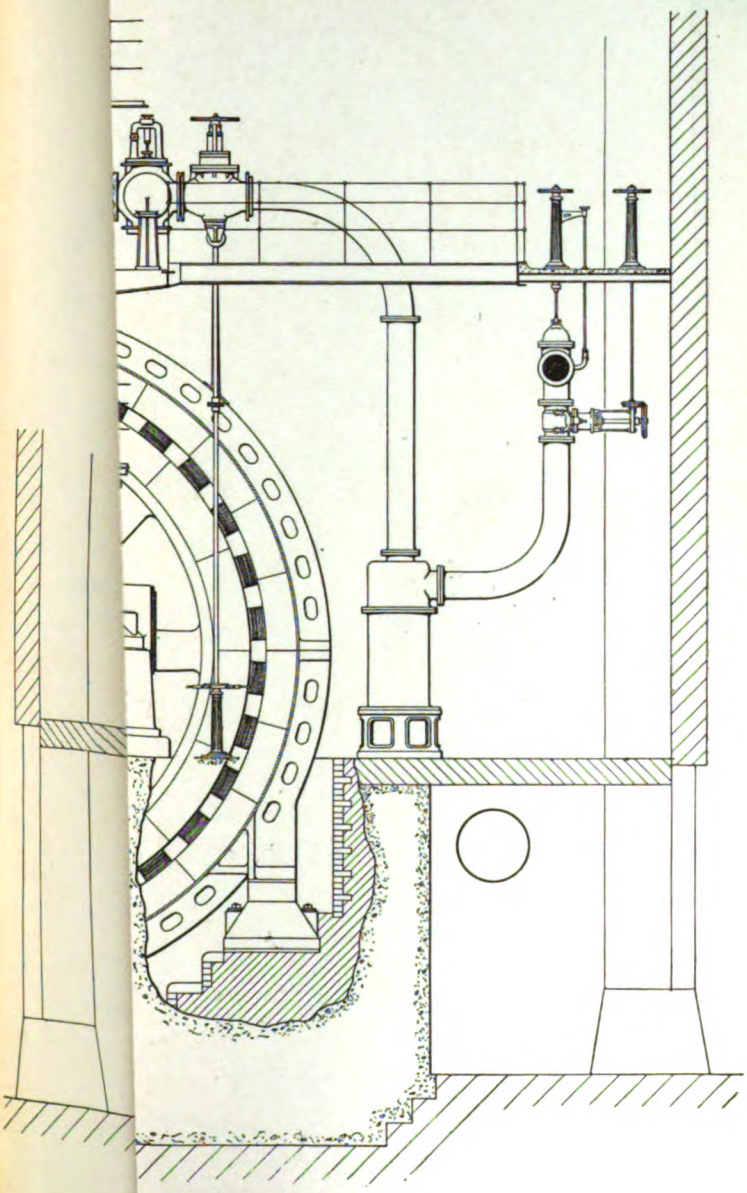

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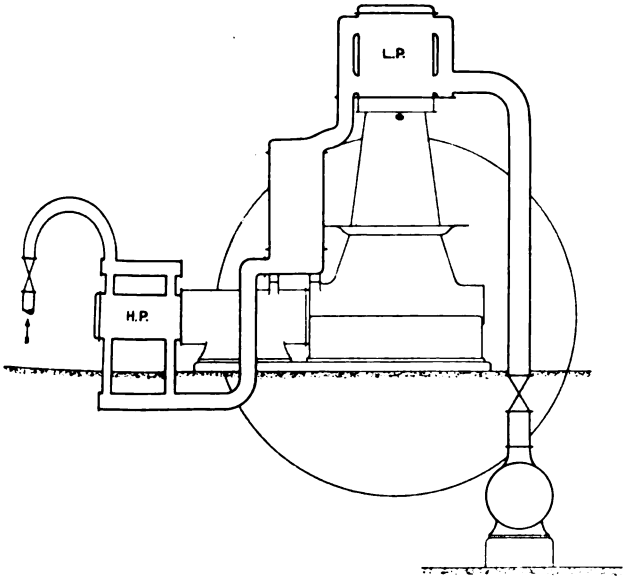

FIG. 9.—Imperfect Drainage System of American Engine.

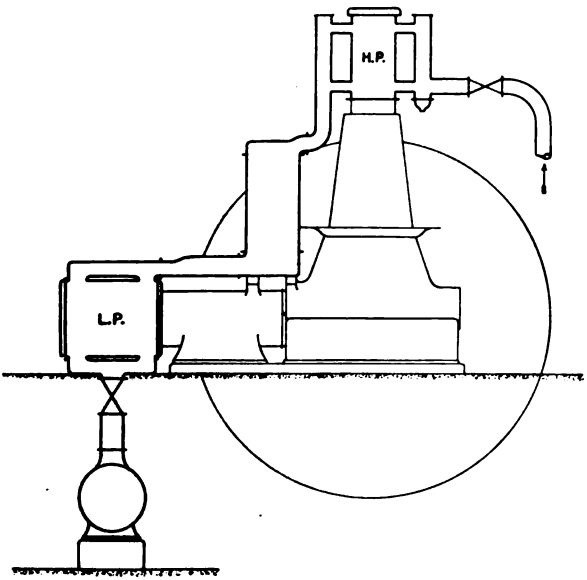

FIG. 10.—Greenwich Generating Station—Natural Drainage of Reciprocating Engine.

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from its own steam separator on the engine-room floor, and there is a stop valve for each steam admission. The two stop valves are coupled together by a cross shaft, so that the attendant can open both admissions from one place. There are no steam or water pipes crossing the alternator from one side to the other.

Each low-pressure cylinder has its own condenser and air pump in the basement, the positions being as shown in Figs. 7 and 8. The condensers are of the ordinary surface type, and each contains about 4,500 sq. ft. of cooling surface. The water supply is given from the common circulating system described later.

The air pumps are of the 3-throw Edwards single-acting pattern, with plungers 16 in. diameter by 14 in. stroke. They run at 100 revs. per minute, and are driven through rawhide spur gearing by a 3-phase motor of 22 B.H.P. running at 375 revs. per minute. The condensed water is pumped into the feed-water tanks in the basement of the boiler house through Lea water recorders, by means of an auxiliary 6-in. ram pump, worked by an overhung crank on the air-pump shaft.

It was mentioned earlier that the condensed water from the reciprocating engines is treated by Harris-Anderson purifiers before entering the feed-water tanks, but Baker oil separators are used in addition in the exhaust pipes between the low-pressure cylinders and the condensers. These remove the greater proportion of the cylinder oil, leaving the residue only to be dealt with by the Harris-Anderson purifiers, and, by this means, the condenser tubes are relieved of a large amount of oil.

The engine governors are of the ordinary Porter type, and are driven by a link chain from the main shaft. They are adjusted by a sliding weight on a balance arm. The position of the weight can be moved either by hand or by means of a small reversible 3-phase motor, controlled from the switchboard gallery. The whole of the load divisions between the various generators are adjusted entirely by this means.

There is, in addition, an emergency governor on each engine, independently driven from the main shaft, which comes into operation at 10 per cent. above the normal speed, and trips a valve in the main steam supply pipe. This valve can also be tripped from the switchboard gallery by pressing a button.

The two cranks at the opposite ends of the main shaft are set at 135° apart. The result is that the four cylinders give eight equally spaced impulses per revolution, as will be seen from Fig. 11. Each half-engine is equivalent to a 2-cylinder engine with its cranks at right angles. The turning moment is so good that no flywheel other than the revolving part of the generator is required. This has a flywheel effort of 16,000,000 ft.^{2} lbs., and the angular variation in the velocity does not exceed 0·15 per cent. up or down.

The generators are of the revolving field type, with 32 poles. They deliver 3-phase currents at 6,600 volts between phases, and 25 complete cycles per second.

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The magnets are built of laminated steel stampings, held in dovetailed slots on the rim of the wheel. They are kept in place sideways by heavy steel side plates and rivets, which go right through them and

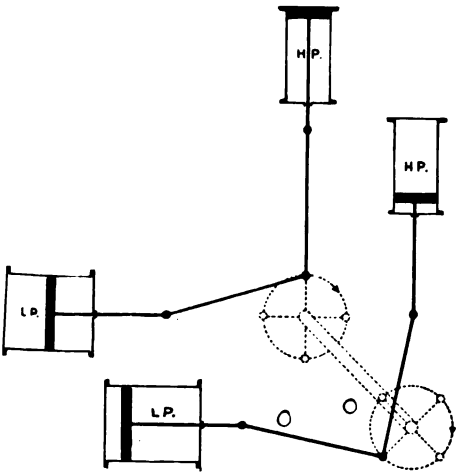

FIG. 11.—Greenwich Generating Station—Diagram of Crank Arrangement.

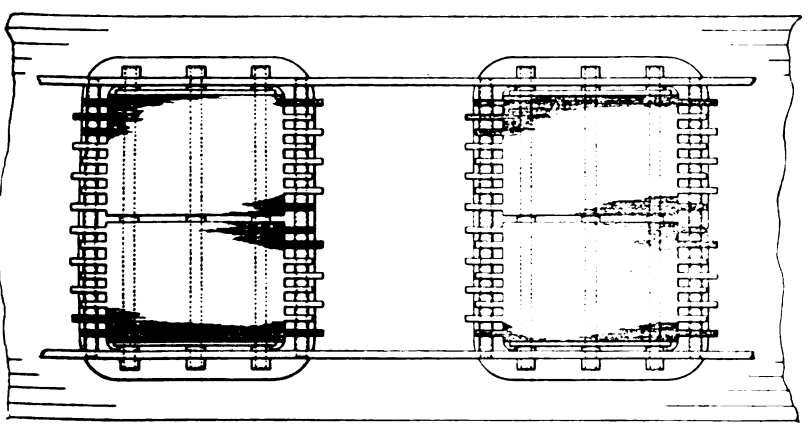

FIG. 12.—Greenwich Generating Station—Alternator Pole-tips.

through the wheel. The magnets are wound with bare copper tape, one layer deep on edge, and the pole-tips are divided up in the manner shown in Fig. 12, with the object of tapering off the field. Damping coils are used, consisting of a copper ring fixed right round the outer edge of the pole-tips on each side, with copper rivets going through

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the pole-tips from one ring to the other. These are indicated in the Fig.

The field coils are connected to two massive gun-metal slip rings mounted on the shaft, and the exciting current which, at full load, is about 400 amperes at 125 volts, is taken through quadruple carbon brushes.

The stator core has open slots, 5 per pole per phase. The coils are former wound, and have 15 conductors per pole per phase, or 3 per slot. The coils are held in place by hard wood wedges, fitting into locking grooves at the tips of the slots.

The stator coils are star connected, and the centre point is earthed in the manner more fully described in the switchgear section later.

Each alternator has its own independent exciter, driven by ropes from a pulley on the main shaft. The exciter is of 50-k.w. capacity,

TABLE III.

No. 4 Set (August 27, 1906).

	Full Load.	Half Load.
Duration of test	6 hours	3 hours
Average steam pressure at stop valves ...	180 lbs.	181 lbs.
Average steam temperature at stop valves	460° F.	446° F.
Average revs. per minute	94·46	94·81
Mean total indicated horse-power ...	5,315	2,622·9
Mean total kilowatts	3,494	1,780
Total water from all sources	353,909 lbs.	89,049 lbs.
Average weight of water per hour ...	58,984 lbs.	29,683 lbs.
Water per indicated horse-power per hour	11·098 lbs.	11·31 lbs.
Water per kilowatt per hour	16·88 lbs.	16·67 lbs.
Vacuum	26·74 in.	26·8 in.

shunt wound, and runs at 450 revs. per minute. A rope-driven exciter was adopted in preference to a direct coupled exciter, because of the difficulty of finding room for such a large machine on the main shaft at a speed of 94 revs. per minute.

Barring gear, of the ordinary self-releasing type, is used for starting the engines. It is driven by a direct-current series motor, and operated by a controller fixed close to each of the stop valves.

Table III. gives the results of some full- and half-load tests taken on one of the combined reciprocating sets before taking over.

The engines were built by Messrs. John Musgrave & Sons, Ltd., and the alternators and exciters by the Electric Construction Company, Ltd. They are excellent examples of English work, and have stood the heavy loads put upon them in a most satisfactory manner.

Practically the only trouble which has been experienced has been with the high-pressure piston rings. These were originally of

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the ordinary cast-iron Ramsbottom type. They not only wore very rapidly, but were frequently found broken, without apparent cause. Several other types were tried, some of the restricted pattern, others solid, but the best results have been obtained with phosphor-bronze restricted Ramsbottom rings, the copper in the mixture being electrolytically pure. These are now being fitted to the whole of the high-pressure cylinders.

Turbines have been adopted for the remainder of the station, but not for any reason connected with the performance of the reciprocating sets. Conditions of output, space, and price were the only determining factors, but, so far as running is concerned, the author has little but praise for the four reciprocating engines and alternators.

The four turbo-alternators are each of 5,000-k.w. normal output, and 6,250-k.w. output on overload. They run at 750 revs. per minute. The two at work were built by Messrs. Willans & Robinson, Ltd., and Messrs. Dick, Kerr & Co., Ltd., and are of the reaction (Parsons) type, while the two now being erected are built by the British Westinghouse Company, Ltd., and are of the impulse (Rateau) type.

The Willans turbines are of the standard pattern made by that firm, with 98 rows of blades in 11 stages on both rotor and stator. The general arrangement of the turbo-alternator will be seen from Fig. 13, from which the relative positions of the steam inlet, condenser branches, air pumps, etc., will be noticed.

The generators are also of the standard construction of Messrs. Dick, Kerr & Co., Ltd. The fields are of the revolving type with salient poles. The stators have six slots and eighteen conductors per pole per phase. The exciter is carried on an extension of the generator shaft, and is of 37·5-k.w. capacity.

Each Willans turbine has one surface condenser in the basement, with a vacuum augmentor addition, by means of which a 95 per cent. vacuum at a 30 in. barometer is guaranteed with condensing water at 65° F. The air pump is of the ordinary Edwards 3-throw type, with buckets 25 in. diameter and 14 in. stroke, running at 95 revs. per minute. It is driven by a 3-phase slip-ring motor of 50 H.P. running at 375 revs. per minute, through double helical machine-cut gearing.

The author regrets that, as the full-load steam consumption tests have not yet been made, he is unable to give particulars in this paper. The guaranteed figure is, however, 15 lbs. per kilowatt-hour, with steam at 180 lbs. pressure superheated to 550° F., and a 95 per cent. vacuum. No bonus is offered for better results than this, but a penalty will be incurred if the results are worse.

In the author's opinion a number of the blade-stripping troubles which have been experienced with reaction turbines in the past have been largely due to striving after low steam consumptions. What should be really desired is perfect immunity from blade troubles under all possible conditions of working, as the financial result of a shut-down of a big set is not to be measured by the cost of the repair so much as

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by the loss due to the disorganisation of traffic or the failure of the supply. A reputation for absolute continuity of supply is worth a great many pounds of coal per annum.

The Westinghouse "Rateau" turbo-generators, while giving the same general output as the Willans-Dick-Kerr machines, are of the impulse type, and have a number of interesting features.

At the present moment these turbines are in course of construction, and the author regrets that it is not possible to give details either of their dimensions or of their performance.

The generating plant in the engine-room is completed by two Belliss-Dick-Kerr direct-current sets of 150 k.w. each, running at 375 revs. per minute. They work at 125 volts pressure, and are used for the station incandescent lighting, for the low-pressure supply to the boiler feed pumps, the switch-operating gear, and as a standby for exciting. Both Belliss sets exhaust into a common condenser.

Switchgear.—The switchgear was very fully described in a paper read before the Glasgow Local Section of the Institution on February 12, 1907, by Mr. Frank Walker, Associate Member. An abstract of the paper was printed in the *Journal* of the *Proceedings* of the Institution, part 183, vol. 38, and the author therefore does not propose to deal exhaustively with it in this paper.

The high-tension switchgear is of the electrically operated, remote control type, and is arranged on two galleries on the east side of the engine-room. It was made by the British Westinghouse Company at Trafford Park, Manchester. The general diagram of the high-tension connections is shown in Fig. 14, from which it will be seen that provision is made for 8 generators and 32 feeder circuits in 8 sections.

The arrangement of the high-tension switchgear may be briefly described as follows:—

A 3-core cable comes from each generator to a trifurcating box on the first gallery, where it is divided into three separate conductors, and, after passing through isolating plugs and series instrument transformers, is connected to the generator oil switch on the second gallery. Following on from the other side of the generator oil switch are isolating plugs, the connections to the main busbars, further isolating plugs, and then the section oil switch. Beyond the section oil switch are other isolating plugs, and then come the section busbars.

Each set of section busbars controls four feeders through isolating plugs and feeder oil switches on the second gallery, and instrument transformers and isolating plugs on the first gallery. The feeder trifurcating boxes below the isolating plugs connect up to the lead-covered feeder cables. Spark-gaps are fitted to all the feeder circuits.

The generators are connected to the busbars by means of links in the form of isolating plugs, and, in the event of any accident to the main busbars or to the synchronising gear, any machine can be run independently on its own section of four feeders merely by withdrawing these plugs or link switches. This arrangement will be clear from Fig. 14. The busbars are divided on the middle line of the station by

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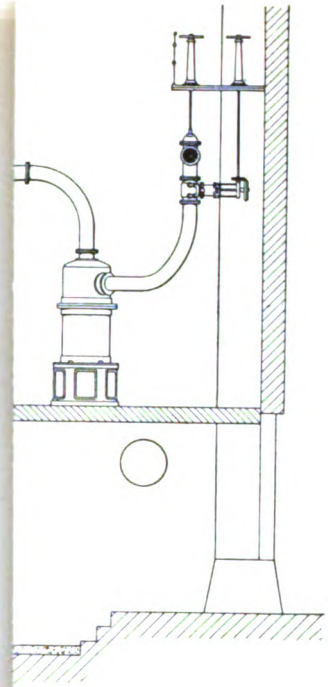

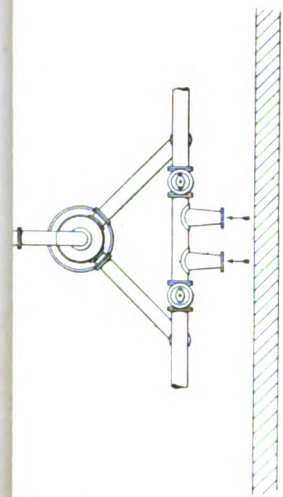

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Turbo-generator.

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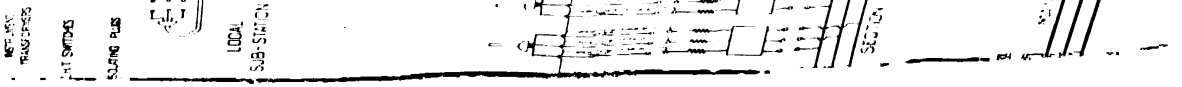

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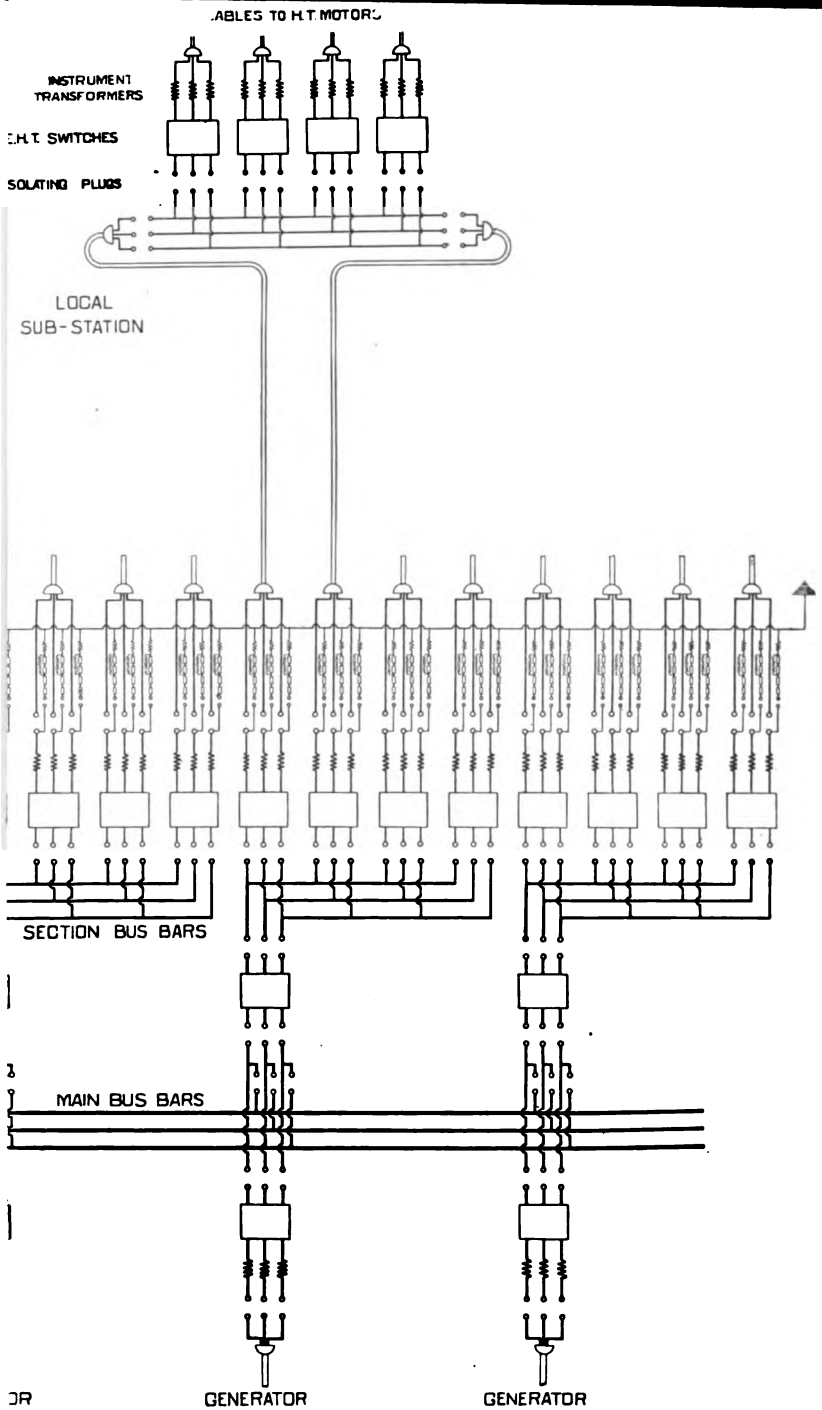

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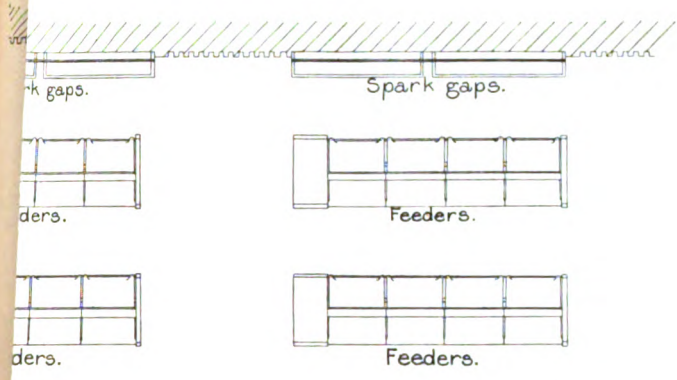

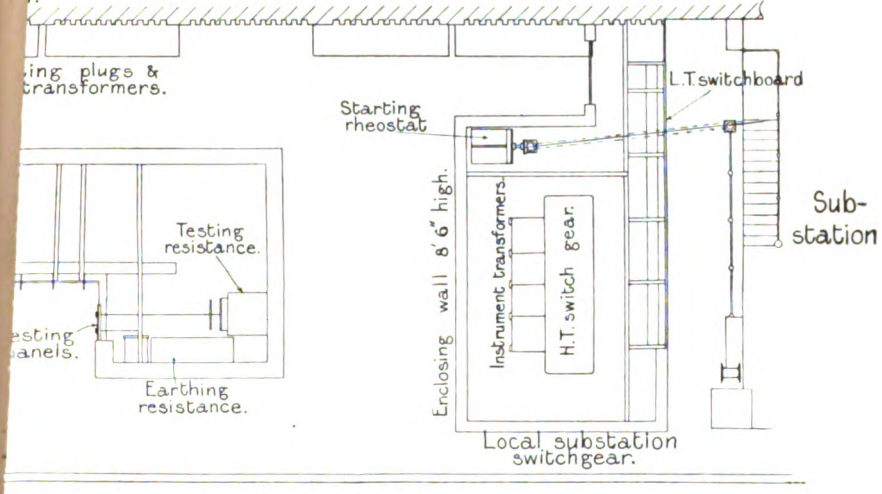

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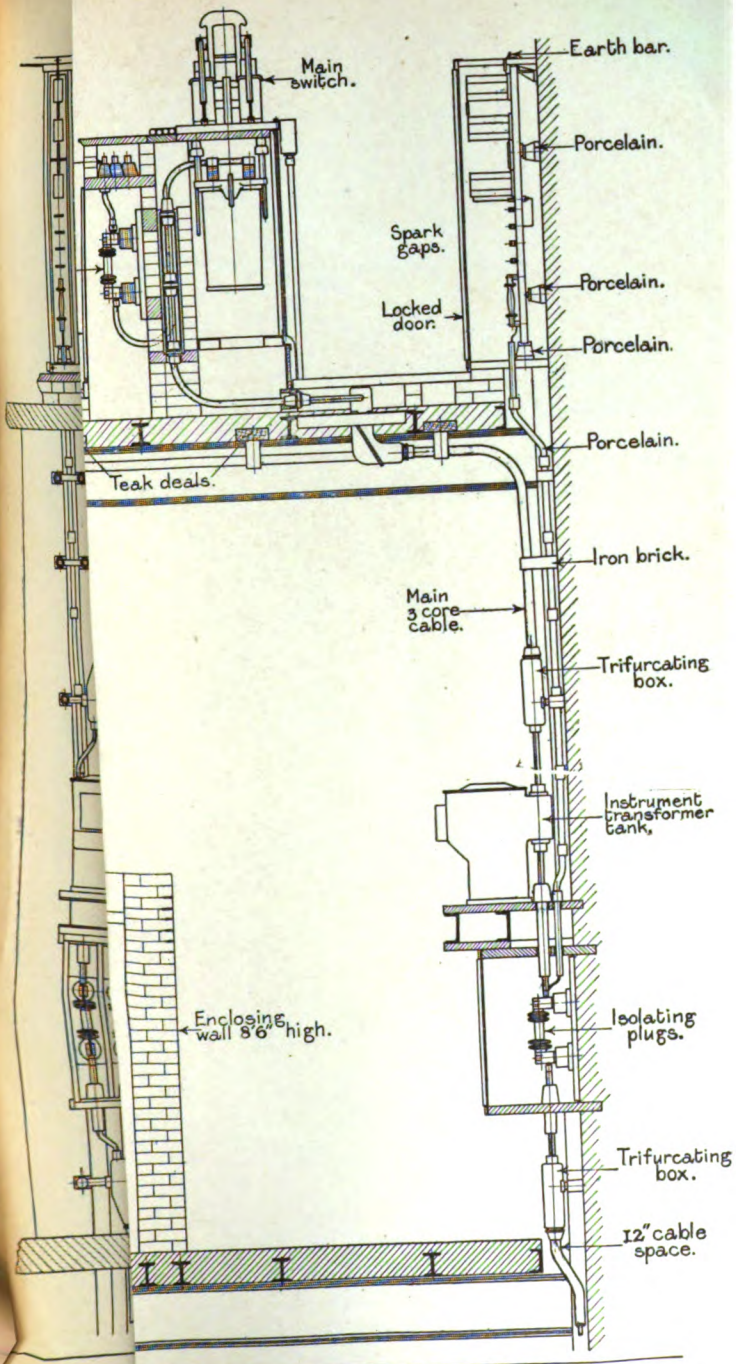

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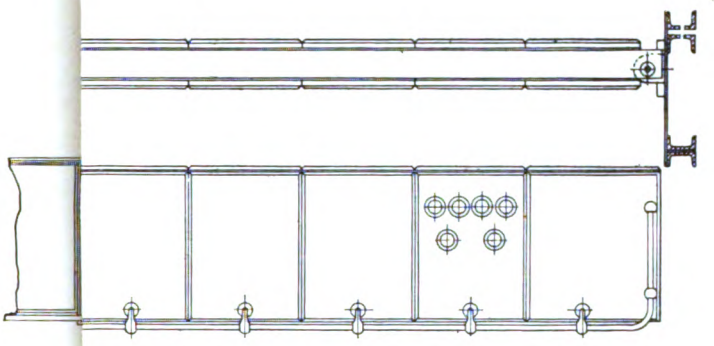
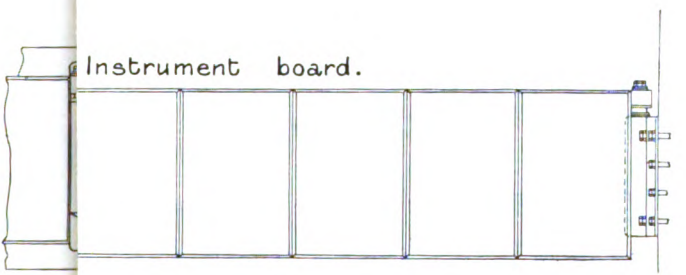
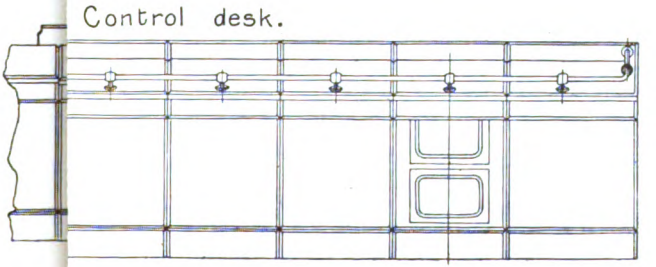


Instrument board.



Control desk.



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a main interconnecting switch, by which the whole of the high-tension switchgear can be divided into two independent sections if necessary.

Fig. 15 shows in plan the arrangement of the two switchboard galleries. The lower gallery contains the control desks, the instrument boards, the generator and feeder isolating plugs, and the instrument transformers. The latter are arranged on the east wall of the station. The upper gallery contains the oil switches with their isolating plugs, the main busbars, and the spark-gaps arranged in blocks of four.

Fig. 16 gives an elevation of one section of the gear on the east wall of the station, and also a cross-section through the two switch galleries, from which the relative positions of the control desks, the instrument boards, the isolating plugs, the oil switches, etc., will be readily seen. Lead-covered 3-core cables are used, wherever possible, for connecting up between the various apparatus comprising the high-tension switchgear.

The isolating plugs are carried in spring jaws mounted upon insulators built directly into the wall, while the instrument transformers, consisting of three series and two shunt transformers for each feeder and generator, are contained in cast-iron tanks carried upon girder brackets built out from the wall. The oil switches are mounted in glazed brick sections.

Fig. 17 gives a plan and front elevation of the right-hand control desk and instrument board. The synchronising panels are mounted upon hinged brackets on the middle stanchion of the station, and two additional synchronising panels are mounted upon stanchions at the extreme right and left of the control desks. In the event, therefore, of the station being worked as two independent halves, by the use of the busbar interconnecting switch, each half has a duplicate set of synchronising panels.

The instrument boards are carried upon hinged brackets on the main building stanchions, with intermediate suspension supports from the floor above. The operator has a complete view of the whole of the engine-room, through the space between the bottom of the instrument boards and the top of the control desks.

The high-tension switchgear has given great satisfaction, as not only is its arrangement simple and easily understood, but it is very convenient for operation. The control switches and instruments for the eight generators are brought to the centre of the control desks, being arranged four on each side of the middle stanchion. The greater part, therefore, of the work of the switchboard attendant can be carried out without his having to move far from the central position.

In addition to the synchronising apparatus on the switch gallery, a synchronoscope is fixed near the stop valve of each engine and turbine. This is connected in parallel with the main synchronising gear when required, and the driver is enabled to bring his machine into synchronism with the others by the indications of this instrument, without having to depend in any way upon signals from the switch

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gallery. A very simple system of signals, therefore, only is required, and two large illuminated telegraph boards are fitted, controlled by six small switches immediately under the edge of each of the generator panels on the control desks on the switch gallery, by which the number of the engine and the signals "Slow," "Run up," "On load," "Reduce," "Stop," are given. These switches are indicated in Fig. 17. When the signal "Run up" is given, the driver knows that he has to bring his machine into synchronism, and he therefore watches the indications of his synchronoscope. When the switchboard attendant sees by the synchronoscope on the gallery that the generator is in step, he closes his oil switch, and signals to the driver "On load." The driver then gradually opens the stop valve to the full, and the switchboard attendant, by means of his field rheostat and motor-governor adjustment, divides the load equally among the various generators.

When the signal "Reduce" is given, the driver gradually closes the stop valve, and, as soon as the ammeter indicates zero, the oil switch is opened, and the signal changed to "Stop." A large bell or whistle calls the attention of the driver to any change of signal of the telegraph board.

The governor adjusting apparatus was mentioned earlier as consisting of a small reversible 3-phase motor, and is put into operation by means of a simple reversing switch on the generator panels of the control desks.

Reverse current relays are fitted on the generator circuits and time-limit overload relays on the feeder circuits. Experience with the reverse relays has almost converted the author to the opinion that the generators should have no tripping relays of any kind whatever.

In addition to the high-tension switchgear, Fig. 15 shows, in plan, the position of the switchgear for controlling the auxiliary machines and the motor, lighting, and track-feeder panels. It also indicates the position of the switchgear controlling the motor-generators in the Greenwich sub-station, which is a part of the main station. This gear does not call for any special reference.

Fig. 18 is from a photograph of the switch galleries taken from the opposite side of the engine-room.

It will be noticed from the diagram of connections in Fig. 14 that the spark-gaps can discharge to a common earthing system. This consists of three 19/12 bare copper cables, which connect in three places with the condenser water pipes, which themselves are in direct communication with the river. Until recently the central points of the star windings of the stators of the generators were also directly connected to this earthing system. The experience at Greenwich, however, has been similar to that at other places, viz., that when more than one machine is running heavy local currents are set up between the various machines through this earthing connection, the currents having a periodicity equal to three times the normal.

It was also found that, when an earth connection took place at any part of the external high-pressure system, the heavy resulting current

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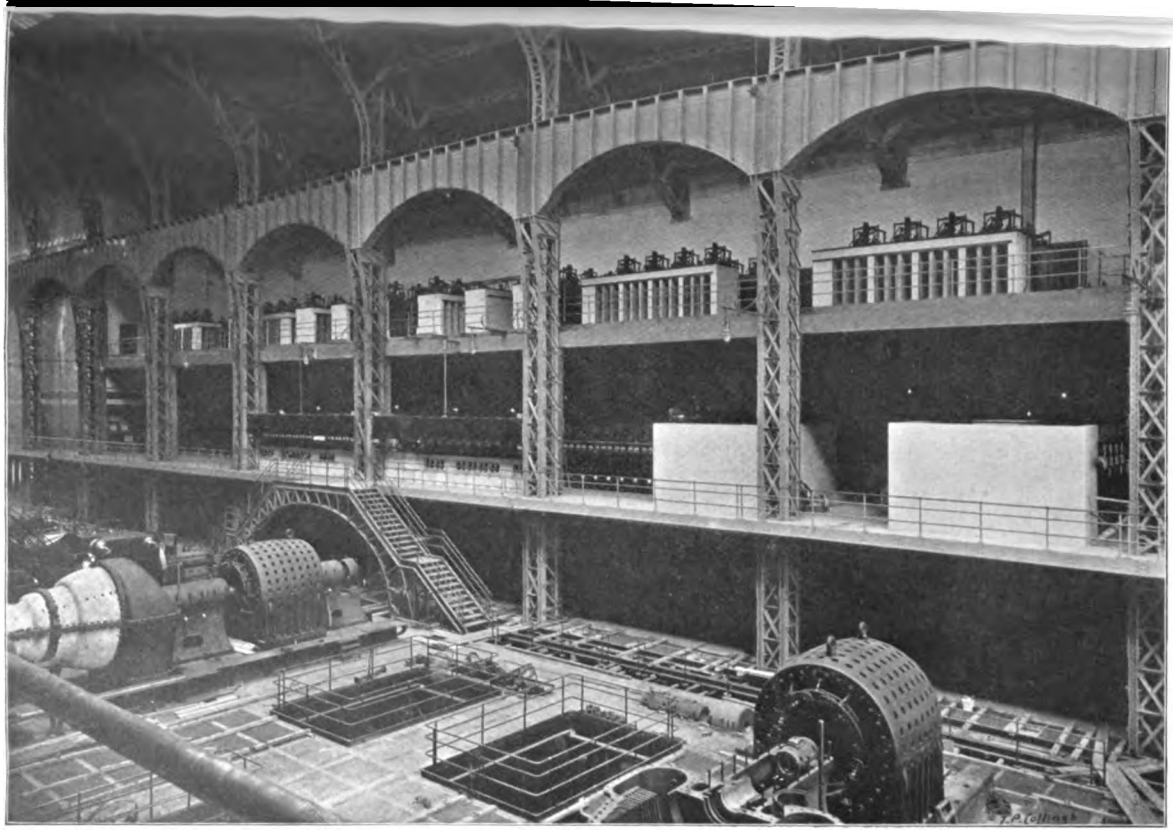

FIG. 18.—Greenwich Generating Station—General View of Switch Galleries.

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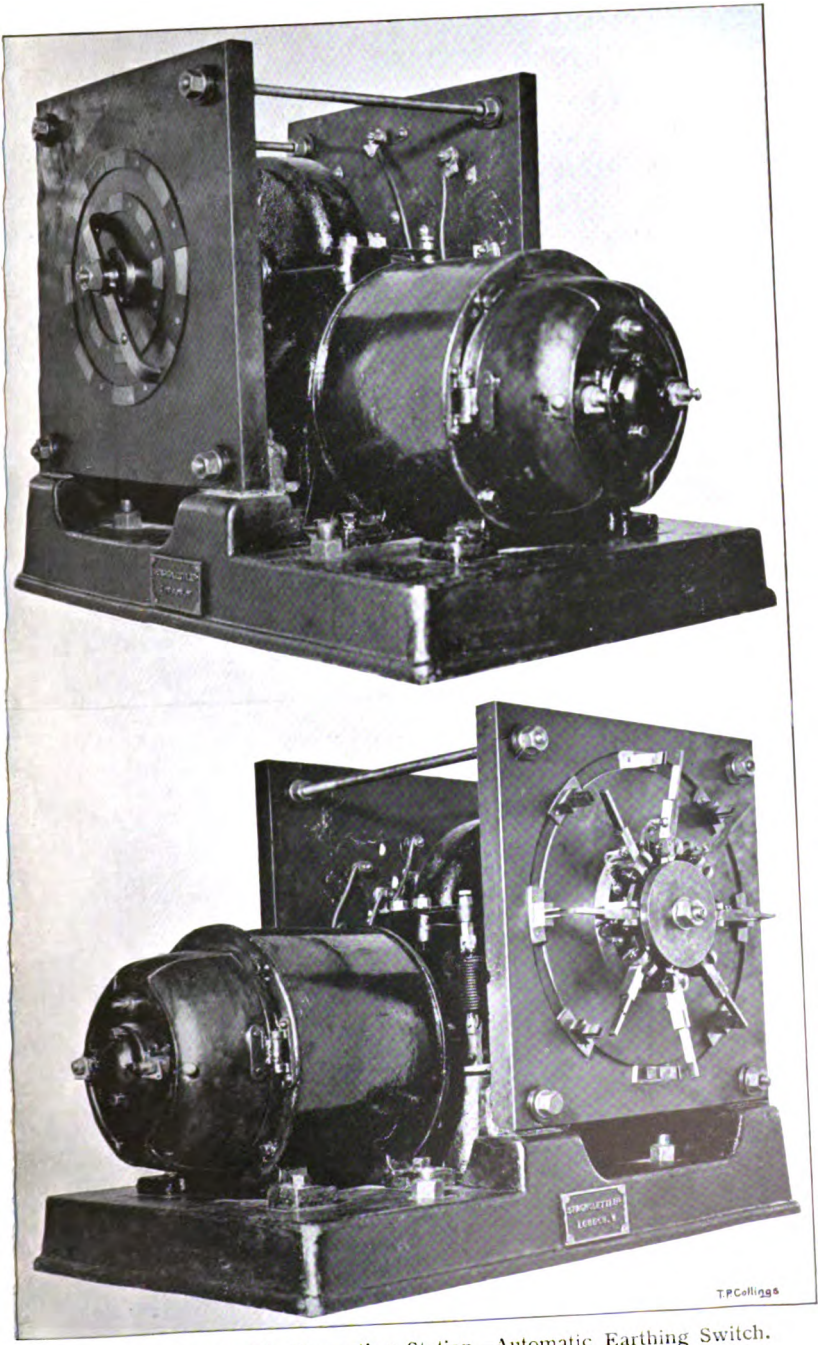

FIG. 19.—Greenwich Generating Station—Automatic Earthing Switch.

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brought the voltage of the whole station down pending the opening of the time-limit overload relay on that individual feeder. The more machines running, the greater was the shock to the whole station, because as each machine was connected to the fault through the busbars, and to the earth connection through the centre of its star winding, they were all working in parallel equally on the fault and on the system.

After a great deal of consideration and experiment, it was decided that a resistance should be placed in the earth connection with a view of limiting the short-circuit current, in the case of a fault, to the minimum amount necessary to operate the overload circuit breaker on the faulty feeder. As, however, feeders up to 10 miles in length are in use, which have an appreciable resistance, the earthing resistance had to be low enough to make the circuit breaker certain in operation, even if the fault occurred at the end of the longest feeder.

The next question was whether there should be an earthing resistance for each generator, or whether the generators should be coupled together at their neutral points with one earth resistance. The difficulties with the former method were that unless the earth connection of each machine was cut off while it was standing, it would be possible, under certain remote conditions, to charge the stator windings of the standing machines to a dangerous pressure in the event of a bad earth fault on the system, and also the high cost of the separate earthing resistances. If a switch were inserted in the earth connection of each machine, there would always be a risk that it might be forgotten either to be opened when the machine stopped or to be closed when the machine started, unless it was locked with the main switchgear. This would have entailed a considerable complication in the arrangement, besides being very expensive. The difficulty with the latter method was that the interchange of current between the machines would not have been prevented.

An attempt was, therefore, made to arrange for only one earthing resistance, and to connect one only of the running machines to earth through that resistance. By this means a short between either phase of any feeder and earth would only affect that particular machine which happened to be connected to earth, and the terminal pressure of the remaining machines would be unaffected. The current which that particular machine would have to give to operate the circuit breaker on the faulty feeder would be well within the capacity of that machine. The danger of this method was, obviously, that if the particular machine which was earthed was shut down, it might be forgotten to connect another running machine to earth.

Mr. E. V. Shaw, therefore, designed the interesting switch which is described below, by which, if any machine which has its central point connected to earth is shut down, either accidentally or purposely, the switch automatically moves forward until it has connected another running machine to earth.

The apparatus is shown in Fig. 19, and consists of two independent

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sets of circular switches, arranged upon two slate panels at opposite ends of a shaft, which is operated by a small direct-current motor through wormgear. The whole is mounted upon a combination bedplate, and forms a complete apparatus.

The switches on one panel are of the single-pole knife type, and are eight in number, arranged in a circle. They are operated by a cam on the end of the wormwheel shaft. These switches control the working of the motor. The switch on the other end of the wormwheel shaft is of the flat spring contact type, and makes connection between two sets of contacts arranged in concentric circles. This switch controls the closing solenoids of the earthing switches of the eight generators.

The cam which operates the motor switches is so arranged that, as the wormwheel shaft revolves, one knife switch after the other is closed. Only one switch remains fully closed at any one time, but the following switch does not open until the one in advance is fully closed. As the motor revolves, therefore, it closes these knife switches one after the other, and so maintains its connection with the source of supply, provided that the other parts of the circuit are complete.

Each of the generator and feeder main oil switches is fitted with a small double-throw pilot switch, which is operated by the motion of the main switch, and is used to connect either a red or green signal lamp. The red lamp lights up when the main switch is closed and the green lamp when it is opened. These pilot switches have been utilised to act as the key switches for the control of the motor.

Fig. 20 shows in diagram the connections of the earthing switches and the circuits and switches controlling them. The action will be clearer if an example be taken. Let us assume that generators Nos. 1, 3, and 5 are working in parallel, and that the earthing switch of generator No. 1 is closed. The diagram indicates the positions of the pilot switches on the generator main switches, and the motor has stopped with the control switches at position No. 1, by which the control current at 125 volts will have closed the earthing switch of generator No. 1 through its solenoid. There is a small auxiliary switch on each earthing switch, which cuts current off the closing solenoid immediately the earthing switch is closed, so that the control current is not flowing the whole time.

Let generator No. 1 be now switched off the busbars. The opening solenoid of the earthing switch, which is separate and distinct from the closing solenoid, is connected in parallel with the opening solenoid of the generator main switch, so that the operation of opening the main oil switch opens the earthing switch on that machine at the same time, and also closes the auxiliary switch. The opening of the main switch also knocks the pilot switch to the "off" position, and it will be seen from Fig. 20 that this will close the motor circuit, and the motor will start to turn the wormwheel shaft, and with it the cam switches and the switch which controls the closing of the earthing switches.

When the motor has brought the control switches to the second position, it will find its circuit still closed, because No. 2 generator is

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switched off, and its pilot switch is set in the "off" position. This maintains the motor circuit, but, when the motor has brought the control switches to No. 3 position, it will stop, since the pilot switch on No. 3 generator main switch is in the "on" position, and the circuit of

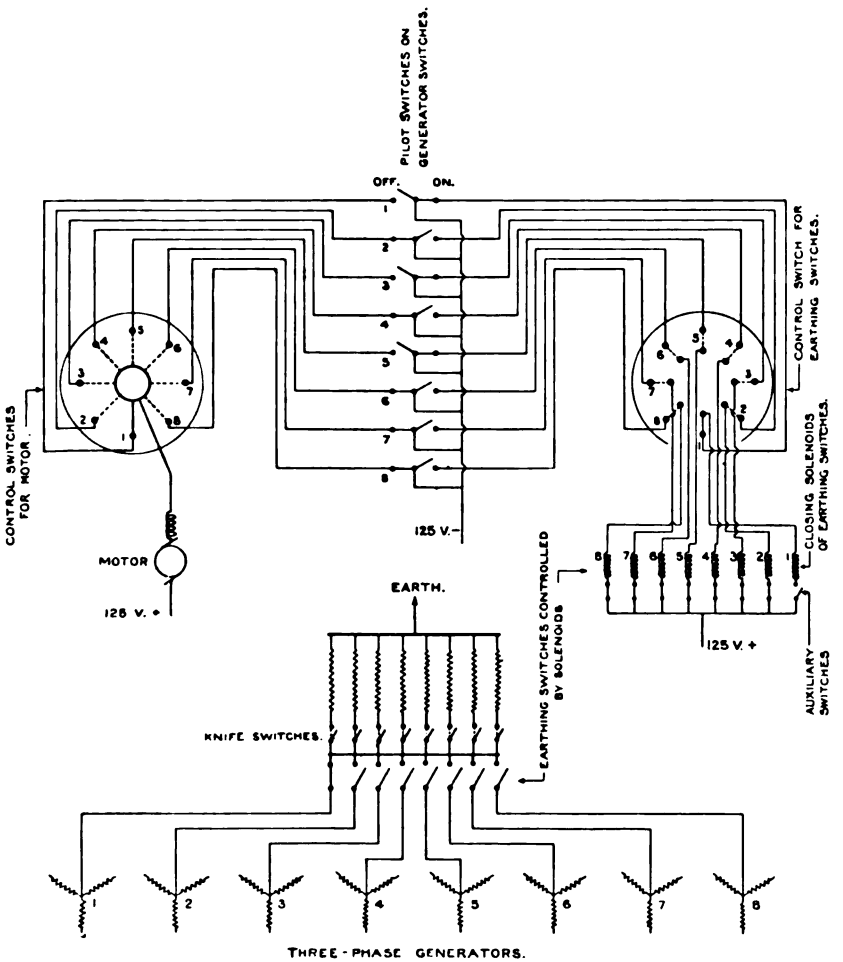

FIG. 20.—Greenwich Generating Station—Diagram of Connections of Automatic Earthing Switches and Resistance.

the motor is, therefore, broken. At the same time the control switch on the other end of the wormwheel shaft will have closed the earthing switch of No. 3 generator, because the pilot switch, being in the "on" position, will complete the circuit of the closing solenoid.

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Should No. 3 generator be switched off, the circuit of the motor would be again closed by the operation of the pilot switch on No. 3 main switch, and the motor would go on revolving the control switches until it came to a generator switch which was in the "on" position, when it would stop and close the earthing switch of that generator. It will be seen, therefore, that this device is entirely automatic in action.

The earthing resistance is made up in eight different sections of cast-iron grids, arranged in 64 frames. The frames are connected eight in series, and the eight sections are joined in parallel. The combined resistance is about 3·5 ohms. A hand-operated knife switch is inserted in each of the eight groups so that either section can be disconnected at any time, either for increasing the value of the resistance or for testing or repair purposes.

The switches connecting the generators to earth are of the single pole oil type, and are large enough to carry 500 amperes for 15 minutes and to break this current at 6,600 volts pressure.

The whole of the operation of the solenoids of the oil switches, automatic motor, pilot lamps, etc., is carried out by direct current at 125 volts pressure, and the supply is taken from either the auxiliary machines or a set of accumulators.

Accumulators.—The battery of accumulators consists of 280 Tudor H.Y. 19 cells of 645 ampere-hour capacity on a 3-hour rating, coupled in series. The battery is worked in parallel with the busbars of the local sub-station, and is used as a standby for the supply, not only to the local track circuits, but also to the 550-volt direct-current power and arc-lighting circuits in the generating station. A tapping at the 125-volt point is taken off, and is connected in parallel with the auxiliary machines, so that there is a standby for the switchgear operation also.

The battery is maintained under contract for a period of ten years on payment of a total sum equal to about 67 per cent. of the original cost. The annual payments are made on the following basis :—

	Percentage of the Total Maintenance Sum.
At the expiration of the second year	1
„ „ „ third „	2
„ „ „ fourth „	3
„ „ „ fifth „	5
„ „ „ sixth „	7
„ „ „ seventh „	10
„ „ „ eighth „	15
„ „ „ ninth „	22
„ „ „ tenth „	35

Condenser Water Supply.—The cooling water for the condensers is obtained from the River Thames. Four 30-in. pipes are laid in the

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bed of the river to a distance of about 100 ft. in front of the coaling pier, and two additional 30-in. pipes are now being laid. Four of these pipes are used as suction (or discharge) pipes, and the other two only as discharge pipes.

The pipes are of cast iron, and are laid at such a level that they are entirely below low-water mark up to the river wall, where they rise vertically and enter the centrifugal pump house. The ends of the pipes in the river are bell-mouthed, and are carried in a concrete basin.

Fig. 21 shows the general arrangement of the six river pipes, the centrifugal pumps, and the straining apparatus. The centrifugal pump house is divided into three portions, that nearest the river containing three fixed strainer boxes, the middle portion containing the centrifugal pumps and the rotary strainers, and the inner portion the valves controlling the various lines of pipes before they enter the engine-room.

The four suction pipes connect through valves to fixed strainer boxes, which are iron boxes containing a coarse mesh grid. Strainer box No. 1 has two suction pipes connected to it, as it is from this box that the larger pump draws its supply.

There are three electrically driven centrifugal pumps, two of 24-in. bore, each capable of passing 12,000 gallons per minute, and one of 27-in. bore, capable of passing 20,000 gallons per minute. The pumps were made by Messrs. Drysdale & Co., of Glasgow, the two smaller ones being driven by Electric Construction Company's 3-phase slip-ring induction motors of 250 B.H.P. at 365 revs. per minute, and the larger by a 350-B.H.P. motor of Messrs Dick, Kerr's make, running at 365 revs. per minute.

Each pump connects directly on the suction side with one of the fixed strainer boxes, and on the delivery side to the inlet of a rotary strainer. Beyond the rotary strainers the pipes pass into the engine-room in three separate lines of 24-in. pipes, cross-connected in the valve house in such a way that all three lines may be fed from any two pumps.

The return pipes from the engine-room are cross-connected in a similar manner before being joined up to the rotary strainers, so that the return water passes through the latter in the opposite direction to the flow. The three discharge pipes then join up to an omnibus pipe, which is connected to the two 30-in. discharge pipes in the river. The omnibus pipe is also connected, as will be seen by the Fig., to the three fixed strainer boxes. When any suction pipe, therefore, is not being used as such, it can be used as a discharge pipe, and, with its fixed strainer, can be washed clear of mud or foreign matter by the discharge water.

The use of Thames water for condensing purposes has frequently given a great deal of trouble in consequence of the large amount of mud which is held in suspension, and the quantities of straw, hair, and other foreign matter floating in it. The arrangement at Green-

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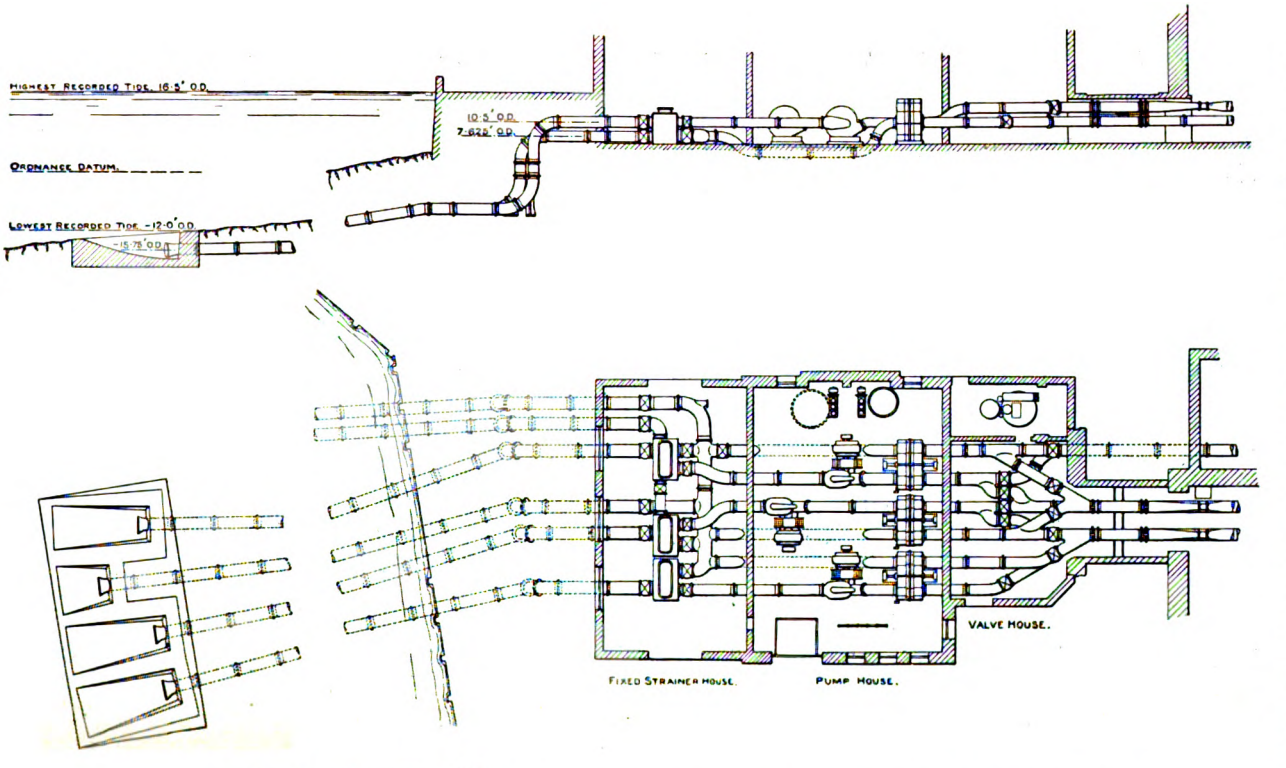

FIG. 21.—Greenwich Generating Station—Arrangement of Condenser Water Pipes, Pumps, and Strainers.

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wich, which was designed on the advice of Messrs. Bailey & Jackson, of the City of London Electric Lighting Company, has proved most effective, and the author wishes to place on record his obligations to them in this respect.

The rotary strainers, which were constructed for the Council by Messrs. Bailey & Jackson, will deal with about 1,000,000 gallons of water each per hour. The apparatus consists of a circular casing some 10 ft. in diameter, and about 5 ft. wide.

In the centre of the casing, and capable of very slow revolution, is a wheel, containing, between its spokes, grids formed of sheet brass strips, interlaced or corrugated in a particular manner so as to form small channels for the passage of water, these channels being about $\frac{5}{16}$ in. in diameter. On either side of the wheel the casing forms a chamber, each of these chambers being divided by a partition of considerable width into two compartments. The first receives the unstrained river water, which, after passing through the strainer wheel, reaches the compartment immediately opposite, and passes thence into the main circulating pipes to the condensers.

The water on its return is led into the fellow compartment on the same side of the casing, and, after passing through the strainer wheel in the opposite direction, reaches the compartment immediately opposite, whence, together with the solid matter previously separated out and temporarily retained upon the strainer surface, it is returned to the river.

The wheel is rotated very slowly by means of a circular rack, about 1 revolution in 2 minutes being sufficient for ordinary conditions of Thames water. The rack is driven through worm-gearing by a small 3-phase motor.

To provide against the wheel becoming choked or jammed by foreign substances getting between the rim of the wheel and the casing, a special form of packing is provided, and sealed with water at a slightly greater pressure than the circulating water. This is found effectually to drive back foreign substance, grit, etc., and to prevent jamming and undue wear between the faces of the wheel and the casing, which would otherwise take place. It will be seen that with this arrangement the circulating pipe system is completely sealed, full advantage of syphon action and consequent saving of power for pumping is obtained, and also that all fibrous refuse is automatically rejected and returned to the river. The only disadvantage is that a certain amount of water, amounting to about 15 per cent., leaks past the partition, and is returned to the river without flowing through the condensers.

The effect of reversing the flow of the water in the fixed strainers and suction pipes has been very successful, and, on a recent occasion, when one of the pipes in the strainer house was opened up in order to couple up one of the new river pipes, hardly any mud or deposit was found, while no trouble has been experienced in the condenser tubes, showing that the rotary strainers effectively prevent all foreign matter

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from passing into the pipe system. The valves in the fixed strainer and valve houses are arranged around the edge of a gallery, and are operated by means of a small portable electric motor and wormgear.

The centre line of the centrifugal pumps is +10·5 ft. O.D., while the centre line of the mouths of the pipes in the river is −15·75 ft. O.D., or 26·25 ft. below the pumps. The lowest recorded tide is −12 ft. O.D., which gives 22·5 ft. as the likely maximum lift for the pumps; while the highest recorded tide is +16·5 ft. O.D., under which circumstances the pumps are flooded. The system of pipes being closed, a syphonic action is obtained, so that, once the pipes are charged, the pumps have only to deal with the pipe friction, and not with the maximum height of suction. A small steam ejector, fixed at the top of the pump, is used in charging. Soon after turning on the steam the water can be seen rising in the gauge-glass of the pump, and the motor is then immediately started.

To relieve the condenser-pipe system of any air which might accumulate, two 6-in. barometric syphon pipes are arranged, which extend about 40 ft. vertically, and are connected at the bottom to the highest points of the pipe system. Two dry air pumps take the air from the top of the barometric pipes.

It will be noticed that all the pipes terminate in the river comparatively close together, and it might have been assumed that there would be a considerable rise in the temperature of the suction water in consequence. Experiments, however, have shown that even at dead low water there is only a difference of 2° or 3° F. between the temperature of the water in the river in front of the pier and in the suction pipes in the pump house. As the tide rises the difference in temperature becomes less until, at high tide, no difference can be noticed. The flow of water in the river is so rapid that the warm discharge water is carried away very quickly indeed.

A large cast-iron sump, about 8 ft. in diameter and 15 ft. deep, has been sunk in one corner of the centrifugal pump house, and into this sump all the drainage water of the station is led. The basement of the station is below the level of the street sewer, so that a direct connection to the sewer could not be obtained. The sump is regularly emptied by means of a small electrically driven centrifugal pump.

The boiler blow-down pipes were originally connected to a sump also, but the enormous quantity of steam which was given off when the boilers were blown down was so objectionable that a new arrangement has recently been devised, which works exceedingly well. It is customary to blow down each of the working boilers every night to an amount of about 5 in. in the gauge-glass in order to keep down the alkalinity of the water. The method now adopted is shown in Fig. 22. A large wrought-iron tank has been fixed in the yard, with a 12-in. pipe at the top connected to the vertical atmospheric exhaust pipe. The boiler blow-down pipes are coupled up to this tank, and all steam which is given off passes harmlessly away through the atmospheric pipe. The tank discharges by gravity into the river through the

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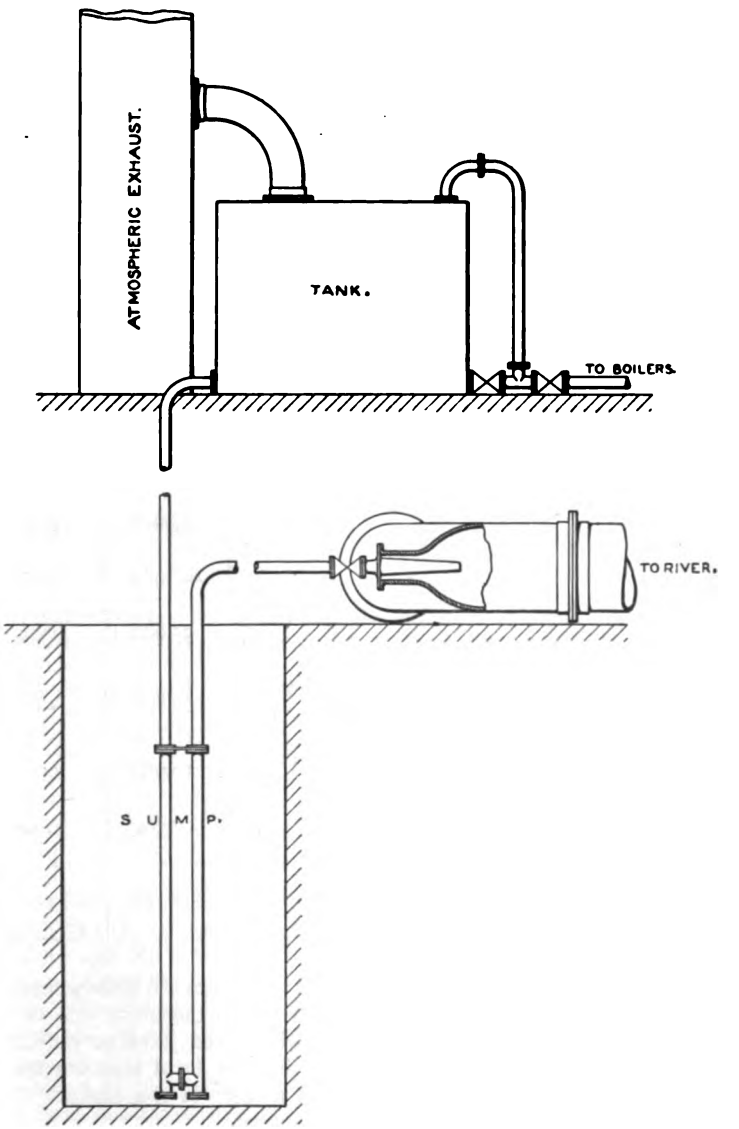

FIG 22.—Greenwich Generating Station—Arrangement of Boiler Blow-down Pipes.

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condenser water discharge system, and air leakage is prevented by means of a syphon, which is placed within the sump mentioned above. There is always enough water left in this syphon pipe to seal effectively the condenser pipe system.

The engine and turbine condensers take their supply of water from the condenser water pipes in the engine-room basement, and the supply is controlled entirely by means of stop valves arranged in convenient positions on the engine-room floor.

The whole of the river pipe-work beyond the strainer house was carried out under the supervision of Mr. Fitzmaurice.

TABLE IV.

	Cost.	Per Kilowatt.
	£	£
Land and buildings	334,000	9·82
Pier and river work	60,180	1·77
Engines, turbines, alternators, and condensers	197,920	5·82
Boilers and economisers	102,460	3·01
Main and auxiliary switchgear, accumulators, station wiring, lighting, tools, etc.	35,600	1·05
Steam, exhaust, and condenser piping, pumps, strainers, and tanks	54,800	1·61
Coal and ash cranes and conveyors, locomotives, etc.	10,950	0·32
Cranes, turntables, railway track, etc. ...	7,560	0·22
Total	803,470	23·63

Sub-station and Workshop.—It will be seen from the general plan of the station (Fig. 2), that there is a sub-station on the south side of the switchgear recess. This is equipped with three 500-k.w. induction motor-generators, and is used for supplying the local tramway tracks and the auxiliary 550-volt direct-current motors in the station. The arc lighting is also supplied from this source.

The workshop adjoining is equipped with such machine tools as are necessary for small repairs, such as a planing machine with bed 3 ft. wide by 6 ft. long, 10-in. and 15-in. lathes, etc.

Lifting Tackle.—A 30-ton electrically operated 3-phase jib crane is

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provided in the yard of the station, and by its means materials can be readily lifted from barges in the river. A railway track laid to standard gauge runs round the whole station, with branches into the condenser pump house, the engine house, and the boiler house.

Hand-operated overhead cranes are fixed in the strainer, centrifugal pump, and valve houses, and a 10-ton electrically operated crane in the workshop and sub-station. The engine-room has a 50-ton overhead travelling crane, worked by four 3-phase motors. The motors are controlled through auto-transformers.

Lighting.—The station is lit by 79 arc lamps, arranged generally in series of five, and about 1,250 incandescent lamps. The latter are on two separate main circuits, the one taking those lamps which are

TABLE V.

		Per Unit.
	£	d.
Coal (including unloading) and removal of ashes	64,797	0·2327
Salaries and wages, running staff	9,840	0·0353
Oil, waste, water, and stores	2,164	0·0078
Repairs to plant and buildings (labour and materials)	5,014	0·0180
Management, insurance, and miscellaneous	1,697	0·0061
Rent, rates and taxes	8,696	0·0312
Total	92,208	0·3311

required both during the day and night, and the other the night lamps only. By this means those lamps which are not required during the daytime can be kept entirely switched off at the main switchboard.

Capital and Operating Costs.—Although the equipment of the station is not quite completed, the total cost is known within very narrow limits, and is, in round figures, £800,000, made up as shown in Table IV.

Owing to the fact that the second portion of the station has only just been put into operation, the full financial effect of working the station as a whole has not yet been ascertained. It is certain, however, that a considerable saving will be made in many directions, although the principal item, that of coal, must always remain the determining factor in the cost sheet.

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The following figures, and Table V., p. 271, are for the year ended December 31, 1908, and relate to the first half of the station only:—

Units delivered to sub-stations	66,836,206 *
Maximum load in kilowatts	16,000 *
Station load factor	47·75 per cent.
Coal	92,672·5 tons.
(Partly at 14s. 5d. per ton, and partly at 11s. per ton.)	
Coal per unit delivered to sub-stations ...	3·1 lbs.

TRANSMISSION, TRANSFORMING, AND DISTRIBUTION SYSTEMS.

The map in Fig. 1 will give a general idea of the area which is fed from the Greenwich station. The high-pressure 3-phase energy is at present transmitted to 13 sub-stations on the south side of the river—viz., Greenwich, New Cross, Elephant and Castle, Brixton, Camberwell, Clapham, Wandsworth, Battersea, Streatham, Stockwell, Tooting, Forest Hill, and Lewisham; and, on the North side of the river, to 10 sub-stations at Limehouse, Shoreditch, Mildmay Park, Holborn, Holloway, Islington, Hackney, Clapton, Camden Town, and Hammersmith. In these sub-stations the energy is transformed by means of rotating machinery to direct current at about 550 volts pressure.

High-pressure Cables.—The general system of transmission is as follows:—

A 3-core paper-insulated lead-covered cable, with conductors 0·15 sq. in. area, runs directly from the main switchgear in the generating station to each of the sub-stations above named. Certain of the sub-stations—*e.g.*, the Elephant and Castle, Shoreditch, and Holloway—have two such feeder cables. The sub-stations are also linked together by a similar cable with conductors 0·075 sq. in. area, forming an interconnecting main, so that each sub-station really has three sources of supply: (1) by the feeder directly from Greenwich, (2) and (3) from the nearest sub-station on either side.

On the south side of the Thames the sub-stations are interconnected in two independent groups, and on the north side in one group only at present.

The 3-core high-tension cables, both feeders and interconnectors, are provided with a copper sheath immediately inside the lead. They are drawn into stoneware ducts which are laid in banks of from 3 to 32, the cables for the north side of the Thames being carried through the Blackwall Tunnel in the cable subway beneath the roadway. Where the cables pass through the manholes they are wrapped with two layers of asbestos tape, painted with asbestos paint, as a protection against an arc in the box on one cable affecting others adjacent.

Sub-station Plant.—The sub-stations which were first built were equipped with 300-k.w. synchronous motor-generators, but all the other

* It is estimated that, for the year ending March 31, 1910, these figures will be respectively 91,000,000 units and 21,000 kilowatts.

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sub-stations with one exception have motor-generators each of 500-k.w. capacity. The majority of these are of the induction type. The actual numbers and sizes of the machines now fixed, on order, or in course of erection are as follows :—

17 motor-generators, 300-k.w. capacity, synchronous type,
58 motor-generators, 500-k.w. capacity, induction type,
6 motor-generators, 500-k.w. capacity, synchronous type,
2 motor-generators, 1,500-k.w. capacity, induction type,
2 rotary converters, 1,500-k.w. capacity, synchronous type.

These machines have been made by Messrs. Dick, Kerr & Co., the British Westinghouse Company, the Electric Construction Company, the General Electric Company, and Siemens Bros. Dynamo Works. The total capacity at present installed or on order is 43,100 k.w., while in the sub-stations already built or projected there is space for further motor-generators of 16,400-k.w. capacity, which makes a total possible plant capacity in the sub-stations of 59,500 k.w. This is calculated to be more than sufficient for the total output of the Greenwich Generating Station, of which the approximate maximum top load is reckoned at 30,000 k.w., as follows :—

	Kilowatts.
Approximate maximum top load Greenwich ...	30,000
Add for diversity factor of sub-stations = (1·25) ...	7,500
Approximate total demand of sub-stations ...	37,500
Add one-third for spare plant	12,500
Total plant required for sub-stations ...	50,000

All the motors have the stators star-connected and wound to take the full-line pressure of 6,600 volts between phases. The central point is not connected to earth.

The magnets of the generators are all shunt wound. Those of the 300-k.w. machines were originally compounded, but shortly after starting the author had the series windings disconnected, and they have since been worked solely as shunt machines. This has simplified the switchgear, and removed certain risks of reversals of polarity in the machines.

The 300-k.w. and the 500-k.w. motor-generators, both of the induction and synchronous type, run at the same speed, viz., 300 revs. per minute, while the 1,500-k.w. motor-generators run at 137 revs. per minute, and the rotary converters at 250 revs. per minute.

The mechanical arrangement of all the motor-generators is identical. They each have three bearings, the middle bearing carrying the short shaft which couples the alternating-current rotor shaft on the one side to the direct-current armature shaft on the other.

Each of the 300-k.w. synchronous machines has its alternating-current rotor excited at 125 volts from a small direct-current generator mounted on the same shaft, while each of the 500-k.w. synchronous

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machines has its alternating-current rotor excited at 550 volts from its own generator.

The whole of the 500-k.w. machines have bed plates with bolt holes arranged to standard dimensions, so that, if necessary, any machine can be taken from one sub-station to another, without having to make any alterations in the foundations. One of the 500-k.w. induction machines is illustrated in Fig. 23, and the synchronous machines are similar in general outlines.

The 500-k.w. induction machines have short-circuited rotors. They are started up from the direct-current side, and, when synchronous speed is reached, are switched directly on to the high-tension busbars. To indicate synchronous speed a small enamelled iron disc, painted with alternate black and white sectors, is screwed to the end of the shaft. When illuminated by a 25-cycle incandescent lamp, these sectors appear stationary if the machine is at synchronous speed. This has proved a most effective method, and is much superior to any type of speed indicator, as it takes into account any variations in the speed of the main generators at Greenwich. When the machine is running on load the "slip" is clearly shown.

The synchronous motor-generators are also brought up to speed from the direct-current side, and synchronising apparatus of the ordinary type is used for switching them into parallel with the busbars.

To start either of these machines in a sub-station which is entirely shut down, a small self-starting induction motor-generator of from 50-k.w. to 150-k.w. capacity is used, which is fed on the alternating-current side from a 3-phase transformer at 220 volts. This transformer is also used for the lighting of the sub-station, and, although the frequency is only 25 ∿ per second, the incandescent lighting is perfectly steady to the eye.

The 1,500-k.w. motor-generators at the Elephant and Castle sub-station have wound rotors with slip rings. A water resistance is inserted across the rings at starting, and the full busbar pressure is switched directly on to the stator. The machine then gradually gathers speed, and the resistance is cut out by degrees, until, when the machine has reached full speed, the slip rings are short-circuited.

Considerable trouble was originally experienced, owing to the breakdown of stator coils on the 500-k.w. induction motor-generators at the time of switching on to the busbars. The breakdowns usually took place between adjacent turns of the terminal coils, and frequently resulted in earthing that particular phase on account of the destruction of the whole of the local insulation. With the exception of machines of one make the fault was common, and was originally believed to occur in consequence of some momentary abnormal rise of busbar pressure when the machine was switched on. Careful investigation with an oscillograph, however, showed no such rise, but rather a slight fall of pressure, which is what would have been expected considering the sudden and momentary heavy rush of current. Fig. 24 is from a film taken during the operation of switching in.

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Investigations by others, however, seemed to indicate that the terminal coils of the machines, which under ordinary circumstances would only have to deal with their own comparatively low voltage, were subjected, at the times of switching on, to the full potential

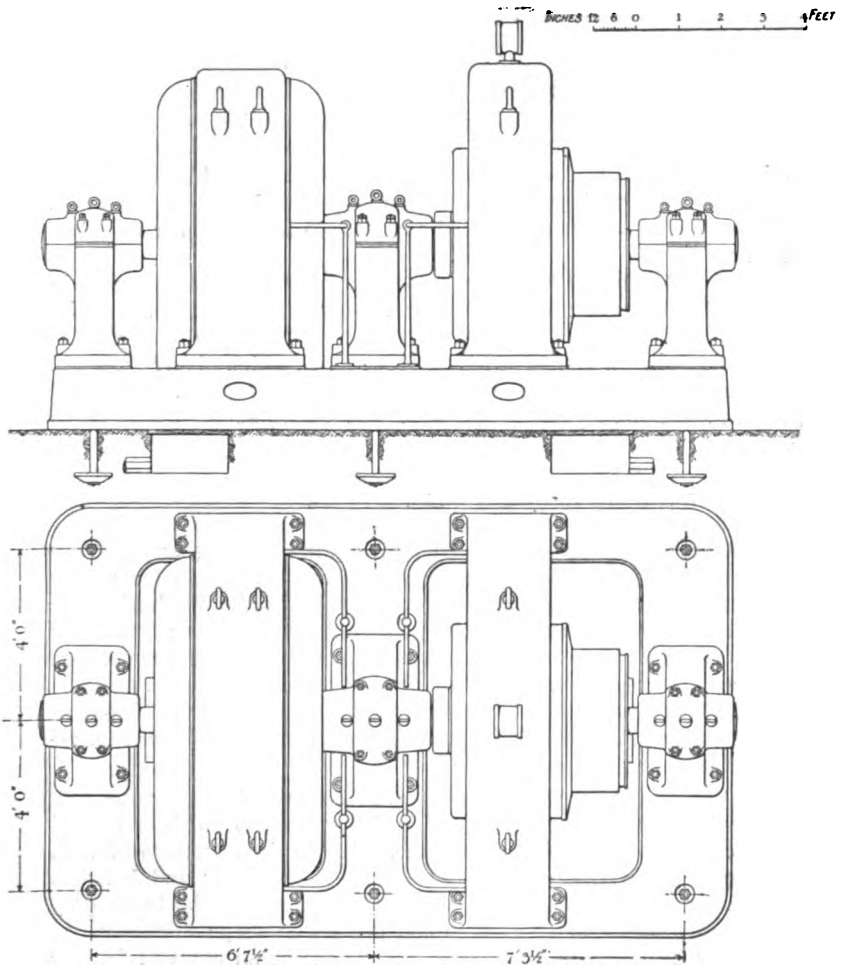

FIG. 23.—Elevation and Plan of Standard 500-k.w. Induction Motor-generator.

difference of the busbars, in consequence of the fact that it took a certain time for the voltage, as it were, to soak in. It also appeared that the terminal coils would be subjected to similar abnormal strains in the event of a bad earth on either of the feeders, which might have

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the effect of suddenly lowering the potential at one terminal of the machine down to zero.

Extra insulation was therefore placed between the respective turns of the terminal coils, and this had a marked effect in reducing the trouble. It was, however, not entirely cured, and the fact that the machines of one particular make did not suffer in this way, although the coils were hand wound, led to the conclusion that the proportions of the coils, and the manner in which they were constructed, had a good deal to do with the trouble.

With the exception of the coils of the machines just mentioned, the whole of the windings of the induction motor-generators consisted of open-ended former wound coils, made up and insulated in the correct shape before threading through the partially closed slots of the stator. The ends were afterwards joined together so as to form a complete coil.

Coils with five different arrangements of the conductors were in use, and these are indicated in Fig. 25. It will be seen that, with the exception of the coils of type A, there was a considerable difference of potential between certain of the adjacent turns, which difference could become seriously aggravated when switching-in took place. It seemed evident, therefore, that the type of coil indicated at A was much superior to the others, and this type has been rigidly specified in all recent machines. That this point had a great deal to do with the breakdowns is evident, when it is stated that there are a number of machines working in the sub-stations with coils of type A, which are tunnel wound by hand, without any special impregnating or insulating material between the layers, and that they have not broken down since they were started, several years ago. Machines with coils having the conductors arranged as at B, C, D, and E in Fig. 25 have frequently failed although they have been semi-former wound, and special care was taken as regards the insulation between the various turns.

The following standard specification is now enforced for all motor-generator coils, whether of the induction or of the synchronous type :—

> "The stator windings to consist of one coil of only one turn wide per layer, per slot, and to be made into partially formed coils before inserting in the slots. The straight portions of each coil to be thoroughly insulated, both externally and between layers, with mica, and the whole of the coil to be thoroughly impregnated under vacuum and pressed to shape while hot.
>
> "The straight portions of the coils to be an exact fit for the width of the slots after the coils have been hot pressed, and to be evenly threaded through the partially closed slots of the stator. Any space remaining radially to be closed up by accurately fitting wedges driven right through the slot at the periphery.
>
> "When in place the open ends of the coils to be joined up and well insulated. The external loops of the windings to be well taped and varnished, and to be finished all over with an oil and

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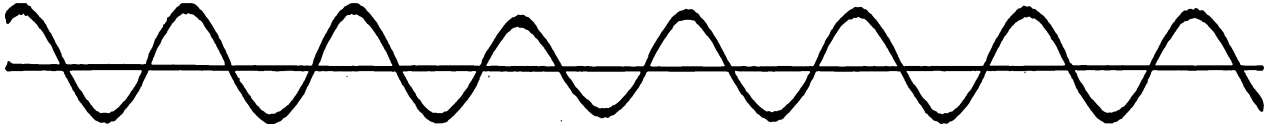

FIG. 24.—Busbar Pressure when Switching in Motor-generator.

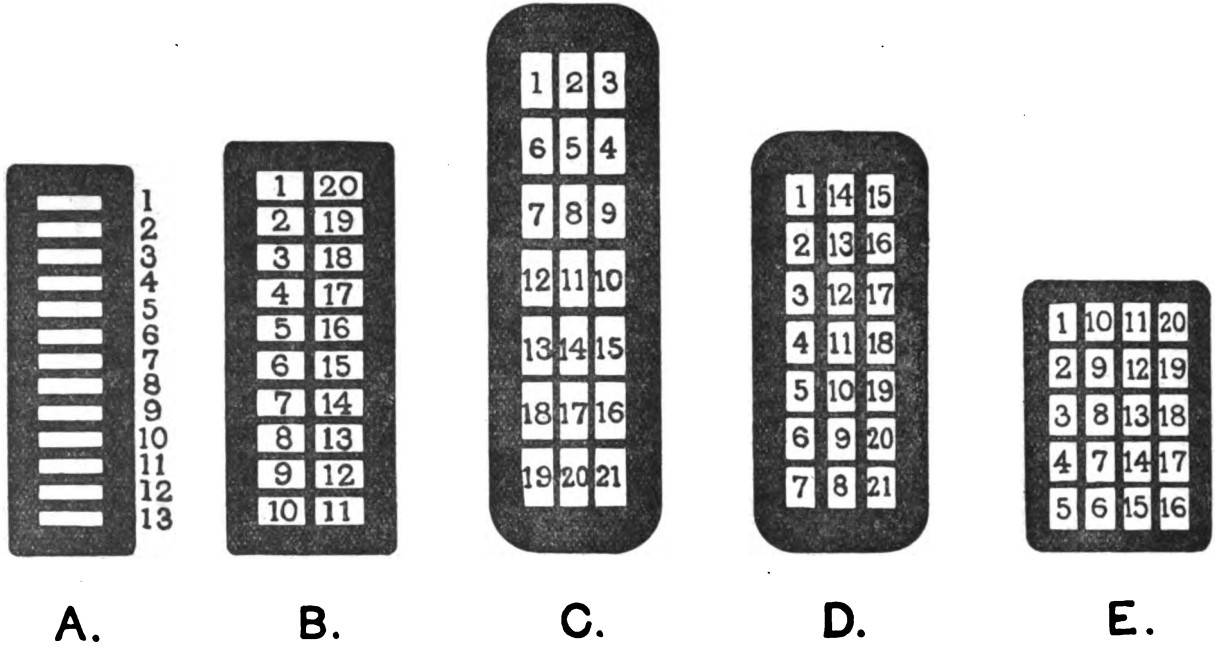

FIG. 25.—Arrangements of Conductors in Stator Coils of Motor-generators by Five Different Firms (Full Size).

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waterproof varnish. If the coils are not stiff enough to stand the mechanical strains which might occur in working, the external loops to be securely anchored in mechanical supports on each side of the core."

Attempts were made by means of an oscillograph to ascertain whether the terminal coils of the machine were actually subjected to the full voltage of the busbars at the instant of switching on, but only a small rise was observed, as will be seen by Fig. 26, which shows the pressure across $\frac{1}{10}$ of one phase at the terminals of a machine during switching. This rise would not account for the frequent breakdowns, and it is evident that the dangerous rises, if they exist at all, only last for such a short instant of time that, even on an oscillograph having a natural frequency of $\frac{1}{3000}$ of a second, no indication was observed.

A series of experiments were then carried out to ascertain whether any benefit would be derived by switching on the induction machines through choking coils which were afterwards short-circuited. This was found materially to reduce the apparent shock of switching the machine on, so far as could be judged by the noise made by the machine. The best proportion of choking coil was obtained when the coil absorbed about one-half of the voltage across the busbars, and Figs. 27 and 28 show the voltage across $\frac{1}{10}$ of one phase at the terminal during the period of switching on a machine in this manner. Fig. 27 shows switching with the choking coil in circuit, and Fig. 28 when the coil was short-circuited. It will be noticed that the oscillograph records a voltage rise as high when the choking coil is short-circuited as when the machine is switched on without the choking coil. A number of such choking coils and short-circuiting switches have since been fixed in some of the sub-stations, and their behaviour is being carefully watched with a view to their general use. So far they appear to have had very beneficial results.

Fig. 29 shows the pressure across one phase of the busbars, and Fig. 30 the pressure between one phase and earth. These were taken with the sub-station fully loaded. Fig. 31 shows the busbar pressure when the feeder was suddenly switched on at the generating station, and Fig. 32 the pressure between one phase and earth under similar conditions. The records were taken at the Shoreditch sub-station, the feeder from Greenwich being about 6 miles long. Only a few faint ripples can be seen in the busbar curves in Figs. 29 and 31, but there is a distinct third harmonic in the other two, evidently due to a want of balance in the windings of the machine.

A 10-ton hand-operated overhead crane is provided in each sub-station, while, at the Elephant and Castle sub-station, where there are motor-generators of 1,500-k.w. capacity, there is a 25-ton, 3-motor crane.

The sub-station switchgear is, as far as possible, uniform in type and arrangement. The operating gear is mounted on a platform, the level of which is about 12 in. above the sub-station floor, on the long

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FIG. 26.—Pressure on Terminal Coils of Motor-generator when Switching in.

FIG. 27.—Pressure on Terminal Coils when Switching in through Choking Coil.

FIG. 28.—Pressure on Terminal Coils when Choking Coil is Short-circuited.

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side of the room. The platform is 11 ft. wide, and the fronts of the panels stand about 6 ft. from the back wall. The low-tension machine and feeder switches are mounted on the fronts of the panels, while the high-tension switches and transformers are erected in brick cells, either in a basement below the switch platform or on a gallery above, and the operating gear only is mounted on the panels.

A plan of the general lay-out of the Shoreditch sub-station is given in Fig. 33. There are five motor-generators of 500-k.w. and one of

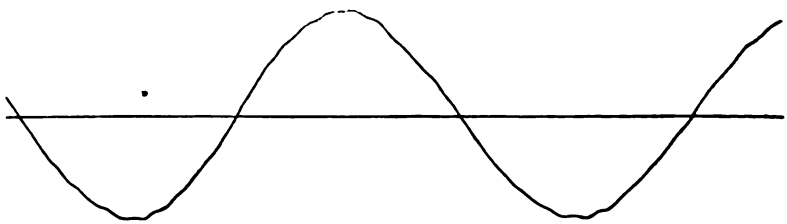

FIG. 29.—Shoreditch Sub-station—Curve of Busbar Pressure.

50-k.w. capacity. This is a "basement" sub-station, and the high-tension switchgear is located immediately beneath the operating panels. The whole of the basement is free for the running of cables, etc., as the machines are carried entirely upon the steel and concrete floor.

Fig. 34 shows a cross-section of the high-tension switchgear of a typical "basement" sub-station, and Fig. 35 that of a typical "gallery" sub-station. The differences in the arrangement of the

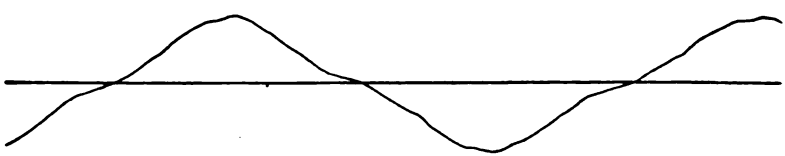

FIG. 30.—Shoreditch Sub-station—Curve of Pressure between 1 Phase and Earth.

gear in the two types will be evident. The gallery type is a cheaper sub-station to build, and the switchgear is more accessible and better lighted.

Every endeavour has been made to obtain machines and switchgear of the simplest possible kind. For this reason induction motors and shunt-wound generators have been largely used, and all instruments and apparatus which were not absolutely necessary have been gradually eliminated. Typical high-tension feeder and machine panels are illustrated in Fig. 36.

A description of the low-tension track-feeder switchgear is somewhat

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FIG. 31.—Shoreditch Sub-station—Busbar Pressure when Switching Feeder in at Generating Station.

FIG. 32.—Shoreditch Sub-station—Pressure between 1 Phase and Earth when Switching Feeder in.

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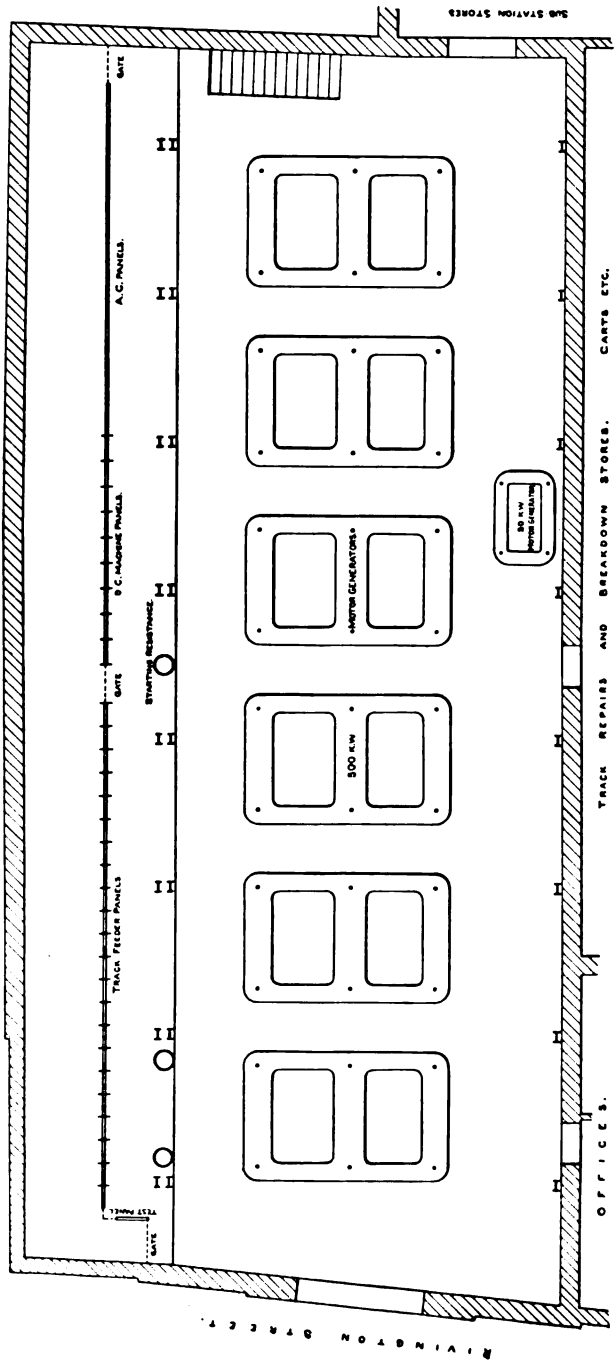

FIG. 33.—Shoreditch Sub-station—Plan of Machine-room.

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bound up with the special arrangements rendered necessary for feeding the conduit system. Two separate conductor bars are used in each conduit, one being positive and the other negative ; the track rails are not used at all. The conductor bars are divided up into sections

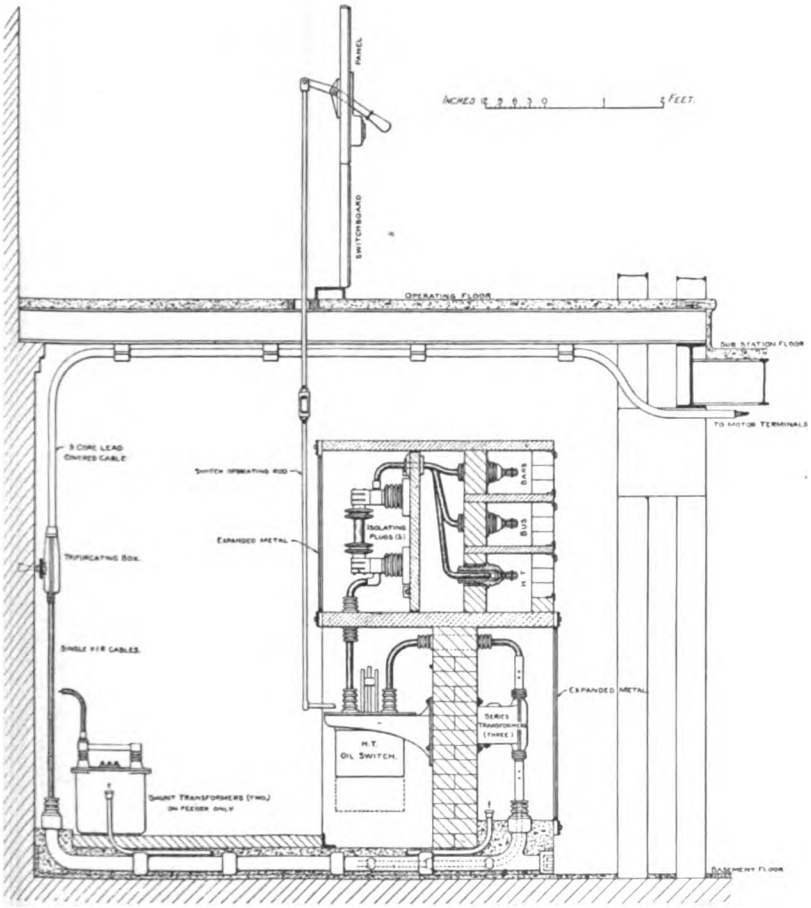

FIG. 34.—High-tension Switchgear in typical "Basement" Sub-station.

of approximately half a mile in length, and each half-mile section is separately fed from a sub-station.

The conduit system is subject to many faults from which the overhead system is free. These faults are sometimes on the cars (generally in the plough), but more frequently are found in the conduit itself, due to foreign conducting substances falling through

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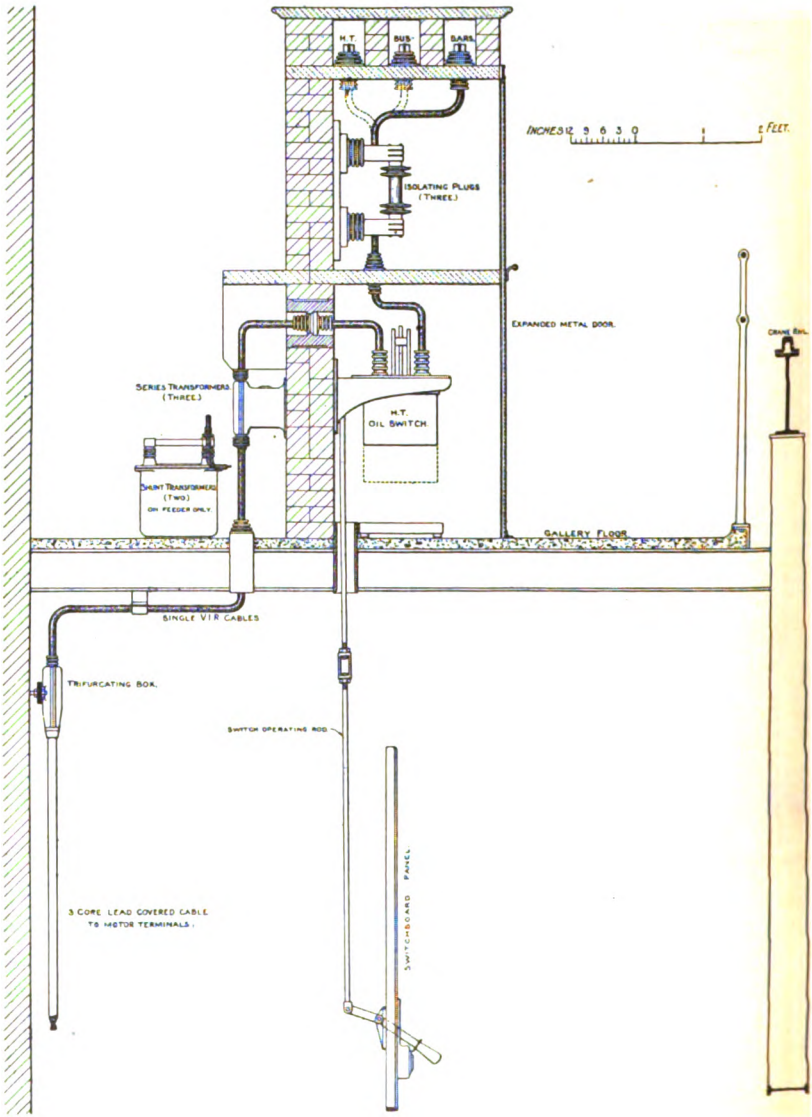

FIG 35. High-tension Switchgear in typical "Gallery" Sub-station.

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the slot rails. As both positive and negative conductor bars are used, positive and negative earths may occur simultaneously on two different sections fed from the same sub-station. These, of course, would constitute a short circuit so far as the sub-station is concerned, and means have to be provided by which the positive fault can be changed at once into a negative fault. This is done by reversing the polarity of the track feeders of the section having the positive earth.

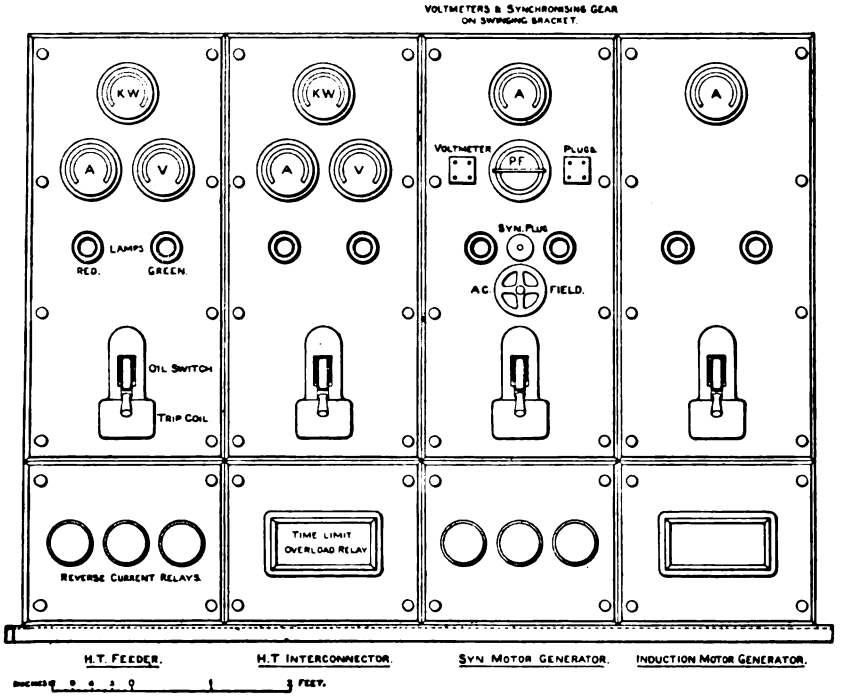

FIG. 36.—Typical Sub-station High-tension Feeder and Machine Panels.

Electrical car and track faults resolve themselves into four kinds, viz., (1) negative earth, (2) positive earth, (3) short circuit between positive and negative without earth, or (4) short circuit with earth. These various faults are detected and dealt with very readily by the type of switchgear adopted.

Fig. 37 shows a front view of a standard track-feeder panel. The characteristic difference between it and one for the overhead system is the use of a double-pole change-over switch. By this switch the polarity of the feeder connected with the panel can be reversed without in any way interfering with the polarity of the busbars or of the other circuits. In the event, therefore, of a positive fault on

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that section, it can at once be changed into a negative fault by reversing the change-over switch. The reversal has, of course, no effect whatever on the running of the motors.

The change-over switch is not of the ordinary kind, but, as shown in Fig. 38, has auxiliary contacts on each pole at the top and bottom

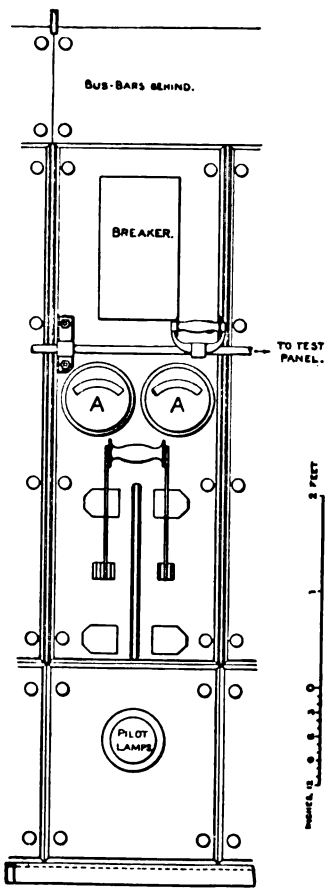

FIG. 37.—Standard Low-tension Track Feeder Panel.

positions. These contacts are insulated from the main contacts, and when the blades of the switch are pulled out of the main contacts into the auxiliary contacts, either at the top or the bottom, the track feeders are connected to the busbars through a fixed metallic resistance of 5 ohms, the track feeders and a special testing panel set at right angles to the main switchgear. The position will be seen from

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Fig. 33, which shows the arrangement in Shoreditch sub-station Fig. 39 shows the diagram of connections.

The negative busbar of the sub-station is connected to earth by means of an adjustable water resistance, which can be varied between infinity and a dead earth. It is usually kept at about 1 ohm.

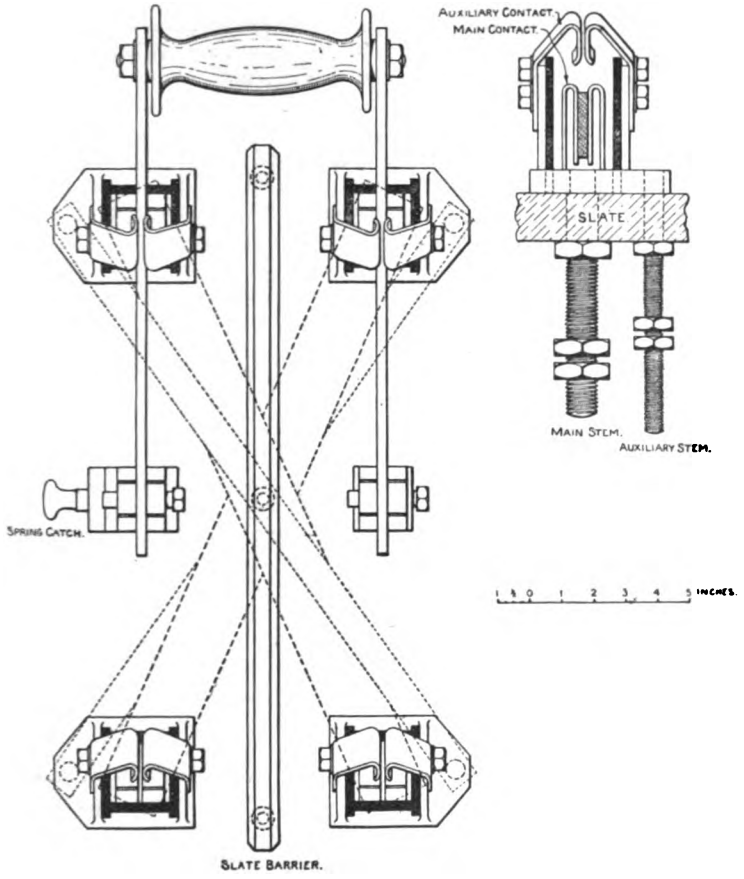

FIG. 38.—Change-over Switch Track Feeder Panel.

All track positive faults, therefore, show themselves at first as short circuits and open the circuit breaker of the track feeder connected to that section. The attendant at once pulls the change-over switch, which is, say, in the top position, into the top auxiliary contacts, and, by means of the handle and connecting rod across the front of the panels, closes the circuit breakers on the testing panel. The indi-

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cations of the two ampere meters on that panel will then show whether the fault is only a temporary one or whether it is permanent, and, if the latter, whether it is a bad earth fault or not. If the fault is a bad one, the ammeters would indicate anything up to 100 amperes, and the attendant can tell whether it would be safe to close the track circuit breaker, or whether he should try the effect of reversing the section.

If the fault should prove a bad one, he reverses the switch to the bottom auxiliary contacts. If the fault were a positive earth, no current would then be shown on the testing ammeters, and the attendant would close the switch in the bottom position. If, however, the fault showed equally bad on that side, he would know at once that there was a short circuit between the conductor bars, which would have to be removed by a speedy visit to the spot in question.

If a fault occurred on the negative side it would not open the track circuit breaker, but the negative ammeter on the feeder panel would at once show a reduced current when compared with the positive ammeter, and a certain amount of current would come back to the sub-station *viâ* the earth ammeter on the testing panel. This would not dislocate the service, but the fault would be searched for and removed at the earliest opportunity. In the meantime the resistance in the negative busbar earth connection would be increased so as to reduce the earth current as much as possible.

The diagram of the testing panel in Fig. 39 shows certain pilot lamps at the top. The lower groups are connected, so that, as long as there is no positive earth, one group lights up brightly and the other is extinguished. Should a positive earth show itself, it is indicated not only by the circuit breaker on its panel opening, but by the dimming of the lamps in one group and the brightening of the lamps in the other. The two upper groups of lamps are in circuit with the auxiliary contacts.

As was mentioned earlier, many of the faults occur on the cars themselves. To locate quickly a car which has a negative fault, a trap is set by permanently reversing the polarity of the track which is nearest to the sub-station. When the faulty car enters that section its fault is reversed to the positive side, the breaker opens, and the attendant is usually able to stop the car on the road and have it sent to the shed at the first opportunity.

The two ammeters on the testing panel which are used for testing the nature of the track faults can be connected by multiple switches to two shunts, so that they will read from 0–10 amperes, and from 0–100 amperes. The lower range is used for testing track leakage when no car is in a particular section, and the higher range for testing faults.

The track leakage of each half-mile section is measured every night at a convenient time between midnight and 3 a.m. The polarity of the section is reversed for about half an hour previously to dry off any dampness on the negative conductor insulators. The leakage between

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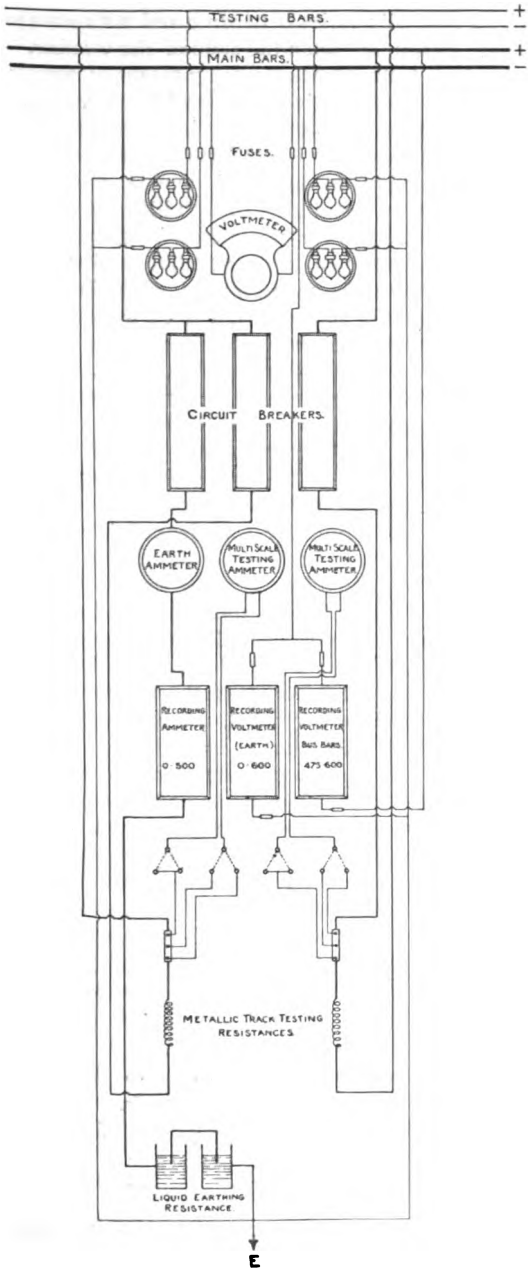

FIG. 39.—Diagrams of Connections, Track Testing Panel.

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conductor bars generally varies between 0 and 2 amperes per half-mile of double track, depending upon the state of the weather.

The method of testing track faults by means of auxiliary contacts and a testing panel was originally devised by Mr. B. M. Jenkin, and although it has been modified somewhat in consequence of experience in working, it remains in its original form in all essential details. Its use has saved considerable time and money, and the sub-station attendants are able to ascertain the condition of the track before closing the breakers, should they open on a fault, in about 15 seconds.

A circuit breaker is shown in the negative busbar earth circuit on the testing panel, but this is not now used, while, in those sub-stations which feed both conduit and overhead lines, the earth connection is removed entirely, as the track rails are connected to the negative busbar. In this case the pilot lamps also are not used.

The various high and low-tension feeder and machine circuits are protected by automatic cut-outs, worked directly in the case of the direct-current circuits, and by transformers through relays in the case of the high-tension circuits. The circuit breakers on the low-tension track panels are of the plain overload type without time limit. Considerable difficulty was originally experienced in obtaining breakers which would stand the very severe work which these are called upon to do, in consequence of the liability of the system to dead short circuits across the conductor bars. Those originally supplied had a brief and fiery career, but those now in use handle their work exceedingly well.

The breakers next in the series are those on the direct-current panels of the motor-generators. These are of the reverse-current type, and, by the use of a separate starting panel, are cut out of the circuit when their motor-generator is being started up.

The high-tension side of each induction motor-generator is protected by a time-limit overload relay, and of each synchronous motor-generator by a reverse-current relay on each phase. The high-tension feeders are protected in the sub-stations by a reverse-current relay on each phase, while at Greenwich they are protected by overload time-limit relays, as was mentioned earlier. As the high-tension interconnecting cables between the various sub-stations are used to transmit energy in either direction, time-limit overload relays had to be used at each end instead of reverse-current relays. The usual settings for the time-limit relays are as follows:—

Low-tension track circuits...	no time limit.
High-tension side of induction motor-generators	3–5 seconds.
High-tension interconnectors	6–7½ seconds.
High-tension feeders, Greenwich ...	10 seconds.

The cost of the sub-stations has depended largely upon the amount which has to be paid for the land. In all cases it has been the aim to locate the sub-station as near to the centre of its work as possible, so as

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to reduce the cost of the low-tension track feeders. As an example the cost of the Shoreditch sub-station is given in Table VI.

The efficiency of the various motor-generators at full load is about 90 per cent., but as the tramway load is a very fluctuating one the all-day efficiency of a sub-station as a converter of electrical energy does not usually exceed 75 per cent. The diversity of the sub-stations—*i.e.*, the ratio of the sum of the maximum loads on the individual sub-stations to the maximum load on the generating station—in any one day is about 1·25.

Low-pressure Cables.—The low-pressure cables are lead-covered paper-insulated single-core conductors. They are drawn into stone-ware ducts, which, when running along the same routes as the high-tension cables, are incorporated in the same banks. The manholes are also, as far as possible, common to both high- and low-pressure cables.

TABLE VI.

Cost of Shoreditch Sub-station (3,000 *k.w.*).

		Per Kilowatt.
	£	£
Motor-generators...	10,400	3·47
High and low-tension switchgear	3,420	1·14
Crane, tools, lighting, etc. ...	400	0·13
Land	10,000	3·33
Buildings *	6,520	2·17
Total	30,720	10·24

* Including offices, stores, etc.

The latter terminate in feeder pillars, which are fixed at half-mile intervals on the tramway routes. At important junctions several feeder pillars are used.

The pillars are somewhat more elaborate for the conduit system than is necessary for the overhead system, as they have to deal not only with two feeders from the sub-station, but with four sets of positive and negative cables going to the tracks. The conductor bars in the conduit are separated by about 2 ft. in their length opposite each feeder pillar, so that the plough breaks contact with one section before it makes contact with the other, and, by means of the switches in the feeder pillars, either the up or down tracks, or both, on either road, can be fed.

From the fact that sections are frequently reversed in polarity from the sub-station, it will be seen that the conductor bars in the conduit are sometimes opposed in polarity at the breaks near a feeder pillar,

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and that if all the switches in that pillar were closed a short circuit would result. The switches are therefore arranged, by means of links at the back of the panel, so that no harm can be done by any ignorant person who may open or close the switches in front.

Fig. 40 shows in diagram the switch arrangements at a feeder pillar under four different working conditions. There are two separate panels, one above the other, each containing four knife switches, two for each

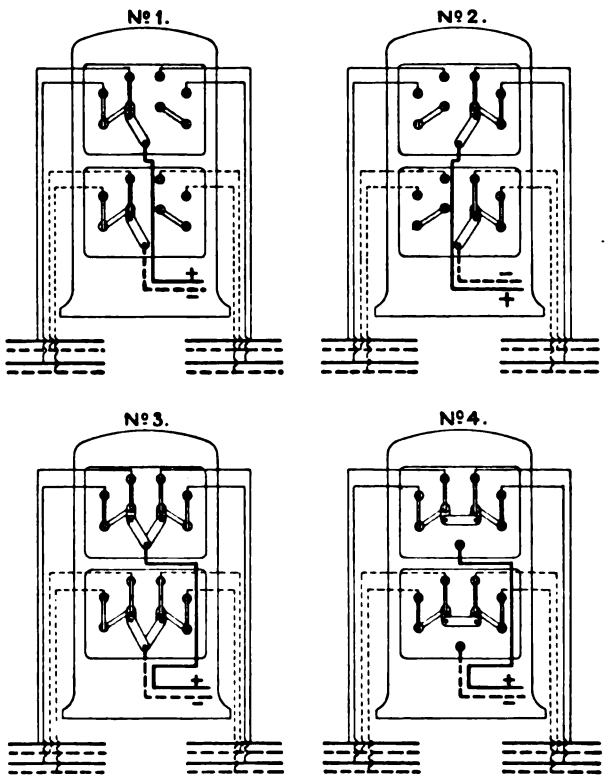

FIG. 40.—Diagram of Feeder Pillar Switching Arrangements.

left-hand track and two for each right-hand track. By special connecting links at the back of the panels and a triangular arrangement of terminals, it is possible to connect up the feeders and the switches in any desired manner. For example, in the Fig. No. 1 shows the feeder feeding only the left-hand tracks, No. 2 only the right-hand tracks, No. 3 both right- and left-hand tracks at the same time, and No. 4 the feeder disconnected and the two sets of tracks linked through. Either No. 1 or No. 2 arrangement is the usual method of

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working, so that each feeder pillar only has to control its own half-mile of track in one direction.

It will be seen from Fig. 40 that any person who may operate the switches cannot do any harm if he should close those switches which should be normally open, because the links at the back which connect those switches to the feeders would have been removed. The changes in the arrangements of the links, which determine the whole thing, can only be made by one of the technical staff, as the doors at the front and back of the panels have separate keys.

Each feeder pillar is provided with a hand telephone apparatus, the lifting of which from its rest rings the telephone bell in the sub-station which feeds that particular pillar, so that the drivers, conductors, or inspectors can at any time speak with the source of the supply.

Vulcanised bitumen cables are used entirely for all connections to the conductor bars in the conduits, whether from the feeder pillars or between sections of the track. As breaks have to be left in the bars at all junctions and crossings, so as to give the ploughs a free passage in either direction, the "jumper" cables form quite an important part of the underground mains system. Owing to their position they are very liable to faults.

General.

Since December, 1903, the London County Council Tramways have been under the management of Mr. A. L. C. Fell, M.I.E.E., the present Chief Officer. In his able hands the system has made wonderful strides, as the following figures will show :—

Table VII.

Electric Traction.

	Passengers Carried.	Car-miles Run.	Receipts	Receipts per Car-mile.	Maximum Kilowatt on Stations.
			£	d.	
1903–4	53,351,840	4,469,576	222,477	11·946	3,700
1904–5	126,255,280	10,931,396	537,754	11·762	5,520
1905–6	141,845,555	12,164,292	612,906	12·093	7,050
1906–7	183,062,063	16,267,579	810,320	11·955	10,890
1907–8	279,166,461	25,591,028	1,252,001	11·742	15,700
1908–9 (estimated)	—	31,800,000	1,550,000	11·700	18,500

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There can be little doubt but that, as the few remaining horse lines are converted to electric traction, and more connecting links between the northern and southern sections are obtained, the undertaking will grow still further, and that the ratepayers of the Metropolis have a most valuable asset in the tramway system.

In conclusion the author takes this opportunity of expressing his sincere thanks to the various members of his staff for their loyal and devoted assistance during the trying period incidental to the inauguration and development of such a large undertaking, and to the Chief Officer for his cordial support and co-operation under all circumstances.

Discussion.

Mr. Bailey. Mr. F. Bailey: I think Mr. Rider has had an opportunity which will fall to the lot of few engineers, in that after considerable experience of generating stations in this country he was called upon to carry out perhaps one of the largest and most important works which has ever been constructed for the purpose of supplying current for tramways. How well he has carried out his task is shown not only in the paper but also in the results which have been attained. Many members have doubtless seen the works, and I myself visited them this morning and found running not only two of the Musgrave engines which are described in the paper, but also the first turbine put in there by Messrs. Willans & Robinson, which was running perfectly on more than full load. It occurred to me at the time how ill-advised people were, when these works were put down, to suggest that what Mr. Rider was then doing was already out-of-date, and I think the results have shown that even if they were out-of-date in any small details he has done his best to keep them up-to-date from time to time. Personally I hope that in years to come not only will the original features be retained, but we shall see Musgrave's engines running long after the turbines have had two or three changes. Mr. Rider differs somewhat from previous writers of papers in another matter which shows his experience, for he has not only taken advantage of any assistance or advice he could obtain, but has actually acknowledged it. I am one of the fortunate people who can speak with some appreciation of Mr. Rider's kindness in that matter, for in connection with the City of London Company we had the pleasure of supplying the County Council tramways with a certain amount of current for some time during the execution of these works. It was a matter of considerable pleasure to us because the account naturally ran into very large figures. The fact that our supply was appreciated is, I think, another sign that even old works are not always antiquated. With the assistance of other companies we certainly kept the tramways going in the way to which Mr. Rider refers, and I think he shows that he, at any rate, appreciated the absolute reliability of the supply. With reference to the general design of the work at Greenwich, there are several features which must strike every one entering the place, par-

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Mr. Bailey

ticularly the colossal magnitude of the undertaking and the open-mindedness with which the architect and the engineer must have collaborated. They do not appear to have been tied down to any particular scheme. It is true they had the encouragement of the rate-payers of London behind them, but I think nobody would suggest they took any unfair advantage of that. The works are of national importance, and are a credit to this country. The design of the iron-work in the engine-room especially should form a study for all engineers. Year after year we have been criticised very harshly by our Continental friends for the very ungainly and unsightly manner in which we put up buildings. I am quite sure that they cannot have seen this roof at Greenwich, which is a most artistic piece of work, and quite worthy of the importance of the undertaking.

With the permission of the Chairman, I should like to make a few remarks on the question of feed water and circulation water. Dealing first of all with the question of feed water, on page 248 the author mentions the use of sulphate of alumina and carbonate of soda and so on for the purpose of softening or coagulating the oil, and rendering the condensed water fit for the boilers again. I cannot help thinking that it seems a pity to use so much soda, because on page 268 Mr. Rider mentions that "it is customary to blow down each of the working boilers every night to an amount of about 5 in. in the gauge-glass in order to keep down the alkalinity of the water." I cannot help feeling that, if it had not been for the use of so much soda, that excessive blowing off would not be necessary. This is a case of blowing down from the blow-off cock, and not by use of the skum cock, which is another matter altogether. While we all appreciate the desire to avoid the water becoming too salt, still it does seem a pity that so much soda should be used and cause such excessive waste. That it is waste I can prove by a small consideration. Five inches in the gauge-glass would mean something like 360 gallons of water at a temperature of 300° F., and the heat units contained in that water would be about one million. If we assume that the coal at 14s. a ton yields 12,000 B.Th.U. and the boiler efficiency is 70 per cent., it follows that 8,400 B.Th.U. are produced from every ton of coal. Working that out, we find that it costs about £530 a year to reduce this amount of salt in the water. That it is absolutely necessary to keep the salt down is perfectly apparent. Quite recently we have been experimenting upon this matter, and we found that the electrical resistance of water in a boiler, even with a comparatively small percentage of salt in it, is a very vital matter indeed. Electrolytic action is immensely increased, and even plates will show action upon themselves, in addition to the very deleterious action on all the fittings of the boiler. It seems a pity that very serious attention has not been generally drawn to this point of avoiding salt in the water at all costs. With reference to the author's most generous appreciation of the work Mr. Jackson and I myself have done in connection with this scheme, we have supplied three rotary strainers for the works at Greenwich. Mr. Rider very kindly accepted our advice

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Mr. Bailey. with reference to laying down a certain portion of the condensing plant, the pipes, and so on. There were several features in connection with this work which we had already had before us for years at Bankside, the works of the City of London Company, where we had lived through a period of great anxiety and trouble in overcoming these very difficult problems. The first point was to get water at all; having got the water, how to keep up the supply, and avoid pumping up straw, fibre, and other deleterious matter, which simply blocked up the whole plant, the condensing tubes, pipes, and so on. The next difficulty was to get the air out of the pipes—not only air, but marsh gas and other poisonous compounds of that sort. The author, knowing something of these troubles that we had had to deal with, showed his experience as an engineer by coming to ask what we would suggest he should do. He showed his further experience by adopting our advice; and now he has shown he can beat all of us by coming forward and acknowledging it. These rotary strainers, I am glad to say, have worked quite successfully. The reason why a fixed grid is useless for this purpose is that the amount of matter in suspension in the Thames water is so great and is so peculiar in character, that an ordinary fixed grid with a 2-in. or 1-in. mesh gets blocked up. The suspended matter accumulates on the grid until the mud comes up behind, and in a few hours the whole thing is plastered up solid, and the pressure on the front is increased. The result is that, sooner or later, the grid collapses, and the accumulation of several hours rushes up into the feeders, tubes, condensers, and everything, and it is a week's hard work to clear up the place again. In our own case there was £50,000 or £60,000 of condensing plant in peril of being scrapped, because we could not get the water to it. A rotary strainer has another advantage, that in dealing with these large quantities of fibrous material it simply returns it to the place it was taken from. The rotary wheel goes round, the return flow of water washes it back into the river, and there is no necessity to handle it. This is fortunate, for it is not a pleasant duty. The mud is very odoriferous, and we have had to pay people rather heavy rates to cart it away. It is just as well to return it to the Thames where this is possible. Then, again, it has been suggested that these strainers are unduly costly and weighty, and an altogether unnecessary complication. I can only say that, at Greenwich and other places where they have to deal with enormous quantities of condensing water, it is quite impossible to put any plant of this nature to work unless it is something very substantial and solid. These strainers weigh about 25 tons each, and as they have to work against a head of about 30 ft., the strength of the casing must be sufficient to stand such a pressure. It is true the pressure is fairly steady, but it is rather excessive at Greenwich, because, if I might criticise a paper which has been so extremely kind to me, the fact is that the head required is more than usual owing to the pipes being a little too small in one or two places, rendering a head of 30 ft. necessary, whereas at Bankside we do it with a head of about 10 ft. The result is that we have no material leakage across the

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strainer, whereas at Greenwich there is a leakage of about 15 per cent. on the whole amount of the circulation water. The cost of this leakage is a small matter when dealing with such a large quantity and with such large pumps. In connection with this matter I might say that it is possible also to alter the arrangement, so that you can apply more than one pump in more than one place, and thus reduce the leakage to any extent desired. The works cover an area of 3¾ acres, every inch of which is occupied, a large part of it by a roof covering an engine-room with a turbine underneath which looks like a mouse in a house. Still, that roof is very fine to look at. But when one considers the revenue of 1¼ million pounds, it works out at £84 per kilowatt of load, whereas we are thankful to get £13 per kilowatt of load. I do not think it is surprising that, with an output of 91 million units and a 50 per cent. load factor, the author obtains the results he mentions in his paper, and we can look forward in years to come to seeing record results under such favourable circumstances. Mr. Bailey.

Mr. B. M. JENKIN: I wish the author had told us of some more of the difficulties he had had and how he overcame them. I think he only mentions two of them—namely, the engine pistons and the windings of the motor-generators. With reference to the latter, I think the arrangement of the winding is of very great importance. I think that besides putting on additional insulation and arranging the windings so as to give the minimum difference of voltage between the turns, one might consider whether it is not worth while trying to prevent the machines being subjected to the great shock that undoubtedly occurs when switching them on. The author mentions that he has tried to ascertain the pressure across the end-turns by means of the oscillograph, with the result that he does not find any excessive pressure occurring. That rather confirms some experiments that we made at one time with Mr. Duddell's help, the oscillograph failing to show any particular rise of pressure, although we got sparking over from spark-gaps, showing that we certainly did get a very big rise of pressure, something like twice the normal, whereas it appeared as quite an insignificant rise on the oscillograph. It seems to me that if this sparking over occurs in a spark-gap the pressure must also be great enough to spark through insulation, and that in a way spark gaps are a surer test of the presence of the excessive pressure than the oscillograph. I see the author is putting choke coils in series with his machines to try and reduce the pressure. We have frequently used an ordinary charging apparatus or a Ferranti water resistance, and in that way it is possible to avoid putting an excessive pressure on the windings at the moment of switching on. It is only at that moment that the machine is subjected to this pressure; but in this case, as in others, prevention is better than cure. When there is the chance of water-hammer in a steam pipe, one does not go to the expense of strengthening the steam pipe; one prevents the water-hammer by removing the water in time. Mr. Jenkin.

I should be glad if the author would say something more about his actual experience of the comparative merits of the different types of

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Mr. Jenkin. motor-generators. He has, I notice, synchronous motors, squirrel-cage and other induction motors, and rotary converters. I gather he has adopted induction machines chiefly on account of their simplicity. He does not say anything about their comparative efficiency beyond giving a general figure of 90 per cent., and he also does not mention the power factor. If he has the figures, it would be interesting to know how sub-stations working with the synchronous machines compare in over-all efficiency throughout the day with those with induction motors and rotary converters, and also what is the general power factor during the day. One feels that, with such a large number of induction motors, he must be loading up his plant with a large, useless current. Another point of interest in sub-stations of this sort is the extent to which it is found possible to use the overload capacity of the motor-generators. That makes a very large difference in the efficiency of sub-stations. We have found on some of the railway sub-stations that we get momentary overloads of perhaps 30 per cent. on the motor-generators, and even more at times; and if the plant will take those momentary overloads satisfactorily just at the peaks, there will be a very much better average load on the machines and a very much higher efficiency. One would like to know how far the author has been able to adopt that method for working his machines at the sub-stations.

Mr. Roberts. Mr. MARTIN F. ROBERTS: I should like to commence the few remarks I have to make by complimenting the London County Council on the very able engineer they have had to design this station for them, and I think we cannot but all feel proud of having such an admirable station in London. A year or two ago I had an exceptional opportunity of visiting Continental stations, and I am quite sure that Mr. Rider's station will bear comparison with any station on the Continent, and that a great many of the best stations on the Continent will not bear comparison with Mr. Rider's. Where a station of such very large capacity has to be designed, an engineer, although he may have exceptional difficulties, also has exceptional opportunities. Many of the features of the London County Council station, and the means arrived at to overcome the difficulties, would not be applicable in smaller stations. Therefore, I think to a certain extent we may look upon the author's arrangements as exceptional. One of the features in which the author's station may be said to be ahead of Continental stations generally is the admirable plan he has for coal conveying. With the exception of Germany, I think we may say that, even where coal is used on the Continent, the coal-conveying plant is not equal to that in England. I should like to mention, with respect to the coal-conveying plant, that it appears rather a dangerous plan to have a live rail at 550 volts on a pier, where, I suppose, sailors and others will land from ships during the daytime, who will not be acquainted with the nature of the rail, and may come in contact with it. That is a possible risk. Another point in connection with the coal-conveying plant to which I should like to refer is that the method of preventing the coal conveyor running backwards, which is said to have been designed by Messrs. Spencer

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& Co., is not quite novel. A similar arrangement was designed by me for continuous lifts, and has been in use for twelve years at the Mount Pleasant Parcel Office. That continuous lift is practically equivalent to a coal conveyor in design, as it ascends one side and descends the other, and we adopted exactly the same plan of making the links jam in a pair of runners to prevent accidents due to chain breakage. I think the author's work in connection with water pipes might be called pioneer work, because, although he had such admirable assistance from Messrs. Bailey & Jackson, the conditions at Greenwich were somewhat exceptional. I do not think the head of water to which Mr. Bailey referred is entirely due to the size of the pipes, as suggested by Mr. Bailey. Mr. Rider has been kind enough to give me particulars as to how that head is arrived at, and from those figures—which, unfortunately, I have not with me—I did not form the opinion that it could be avoided by using larger pipes. In connection with the question of water pipes, I should like the author to give us a little further information as to whether he finds the barometric pipe is really of any assistance. Is it ever necessary to use it, and, if it is used, how often is it used? There is another point on which I scarcely agree with Mr. Bailey, if I may refer to the remarks that gentleman made, and that is his statement that the 15 per cent. of the water passing through the strainer which is pumped to waste becomes a very small item when such a large quantity of water has to be dealt with. I should have thought that, as it is a percentage, the larger the quantity of water the more serious the loss became. Everybody recognises the excellent work Messrs. Bailey & Jackson have done with their strainer; but it has one serious disadvantage, which they will no doubt admit, and that is, that it cannot be placed outside the pump, and consequently does not protect it. It seems to me that to have a strainer outside the pump is a very distinct advantage. The reason the rotary strainer is not put outside the pump is because of the large amount of mixing of the suction and discharge water which takes place in the strainer. If it were outside the pump, instead of 15 per cent. of the cold water being pumped to waste, 15 per cent. of the hot water would be pumped back into the condensers, and the vacuum would suffer. Leaving the question of water, there is an important matter on which I hope the author will give some information at the next meeting, and that is, as to the relative economy of turbines and reciprocating engines. It is true he tells us in the paper he has not made the official tests, but we read on page 256 that the engines are stated to require 16·88 lbs. of water per kilowatt per hour at full load, and the turbines are guaranteed not to exceed 15 lbs. Mr. Rider says that he has studied reliability of working and an absence of breakdown rather than very great steam economy with turbines, on which point I quite agree with him, and I assume that 15 lbs. is the figure which one can rely on reaching. Consequently it would rather appear that the turbines are expected to be more economical than the engines, although Mr. Bailey has suggested that the engines may be at work long after the turbines have been

Mr. Roberts.

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Mr. Roberts. changed. Taking the figure at 15 lbs. against 16·88 for reciprocating engines, I think there was a very distinct reason, apart from the question of first cost, why the author should choose turbines, and possibly he can tell us whether he has found, when the turbines are working in place of reciprocating engines, there is any change in his coal consumption. I imagine he can give us some information on that point without waiting for the official tests of the plant. The reason I ask the question is because we are so often told that although better steam economy may be obtained with large turbines, yet taking into consideration the much larger quantity of condensing water required to obtain the better vacuum to get that result there is really no economy in turbines. If the author can give us a little information on that point, even without giving us the result of the official tests, we shall be very much obliged to him.

ADJOURNED DISCUSSION, APRIL 1, 1909.

The President. The PRESIDENT: We have to-day the pleasure of seeing Mr. Rider, who could not be present last week.

Mr. Ferranti. Mr. S. Z. DE FERRANTI: When the author undertook the work of supplying the London tramways with electrical power for the County Council, he found that the County Council had already made contracts, and had commenced the work of installing what was to be, I believe, their principal generating station in a place which we can now hardly consider as suitable. It was a place to which coal had to be brought by railway, there was a considerable population round about, there were many houses close to it, and it was almost impossible to work condensing, because of the steam given off by evaporative condensers. The author was able to alter the arrangements of the County Council, and to persuade them that what they were doing was not the right thing. In my opinion that was a great achievement on the part of Mr. Rider, and the commencement of a very successful installation. With regard to the work to be accomplished in a power generating station of this kind, there are a large number of difficulties to be overcome in relation to giving the best possible result for the amount of money spent in capital outlay, and upon the running of the plant for the production of the current. Although we are electrical engineers it is interesting to see how much we are concerned with problems that are strictly outside electrical engineering. In looking through the paper with a view to criticising it, I gather that there is great improvement to be made in a few directions. I do not see many directions in which improvements can be made upon the electrical side. The only thing that I would suggest for the consideration of those now at work upon these problems is that there is a great opening for the more economical transformation of electricity at sub-stations. Looking over the whole electrical system, I do not see that we are likely in the future to get anything very much better than the present systems of electrical supply, unless it be in the transformation of high-tension alternating current into continuous

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Mr. Ferranti.

current where it is wanted as such. My reason for saying this is that the efficiencies everywhere are so high. We are getting so near to 100 per cent. in all these electrical efficiencies that with that one exception there is not much prospect of getting better results. But in transforming the coal into mechanical power for producing the electricity we have a very different state of things. The lessening of running expenses is, I think, the great problem of the future. The electrical problem has only been with us for the last thirty years, whereas one hundred years or more have passed since people seriously went to work to improve the economy with which coal could be converted into power. The problem to be solved is that of getting nearer to the efficiency obtained in electrical generation and transformation. The conversion of coal into mechanical power is done at a very low efficiency; and notwithstanding improvements in gas and oil engines, we still find it is necessary, with the knowledge we possess to-day, to generate the bulk of our big powers by means of steam. There are many reasons for this which I must not go into to-night. There is an immense opportunity for improvement in the primary part of the business of generating electricity, namely in making the power cheaply. In the paper you will see that one part of the transformation has been performed very economically. The author gives the efficiency of his boilers on test at practically 79 per cent. I find, however, on looking into the figures, that his gases are going away from the boilers at a not unreasonable temperature, and that they go to economisers. When you take the process of converting the heat units in the coal into steam, you find that the work done in the economisers the efficiency of the conversion system is not 79 per cent., but that it is nearly 87 per cent., this proportion of the energy of the coal appearing in the steam generated. I would like to emphasise this as a very fine result, and one not unknown in steam practice. The engines give the very good figure of 16 lbs. of steam per kilowatt produced. The turbines are possibly giving a little more than this. An interesting thing to notice here is that, taking these tests together, they give a coal consumption of about 2 lbs. per kilowatt, or slightly over. In the station, running for a period of twelve months, however, the coal consumption is at the rate of 3·1 lbs. per kilowatt. You will thus see that the difference between running on test and running with even so good a load factor as 47 per cent. means adding 50 per cent. to the coal bill. This latter is the principal item in the costs, and if the standby loss could be eliminated the figures would be very much better. Of course this is not wholly possible, but it is the direction in which improvement can be made. The standby losses in the case referred to amount to about £21,000 sterling per annum for coal—that is to say the difference between what it would be if you could generate on the test figures and what it is if you generate on the figures of ordinary every-day work. One of the great merits of the oil engine, for example, is that it practically has no standby losses. As I have told you before, the application of the oil engine is very limited in comparison with steam,

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Mr. Ferranti.

for very good reasons, but still it is not a physically impossible thing to bring down very considerably this difference between the test expenditure and the every-day expenditure.

There is one other point to which I should like to call attention, although I forget how far the author emphasises it. I noticed the point, I think, in connection with one of the latest specifications, namely, that it was not so important to have the very highest economy as it was to have the highest reliability. There can be no question that absolute reliability is necessary. The reliability must be as perfect as it is possible to make it, but I cannot say that I altogether agree that reliability should be attained by the sacrifice of the highest economy. If there is any sacrifice it means a defect in the design due to our present want of knowledge, and no doubt that will disappear in time with experience; and then perhaps we shall call for the highest economy, knowing that engineers will have nothing to do with anything that is not perfectly reliable.

I should like to say a few words upon one other point, the question of the cost of plant in relation to the cost of buildings. I should like—you may say I am a contractor and that therefore it is to my interests that I should do so—I should like to have seen less spent on buildings if it had been possible, and even more spent upon machinery if two things could have been accomplished: (1) if a higher economy could have been obtained as the result of spending rather more in first cost and so spending less annually, which would mean a considerable saving in capital; and (2) giving the contractors a greater profit, so that they should be in a position to do what is now done so much abroad, namely to have large funds available for developing future business, for the purpose of carrying out experimental work to produce more efficient machinery, which in its turn means more electricity, which is what we all want. But the position with regard to this condition of affairs is hardly satisfactory. It is very difficult for manufacturing concerns in this country to devote much money to improving their product. In this way the country is apt to lag behind, and improvements in machinery are liable to come from other countries, when we ought to be making them ourselves. I think this state of affairs is very much to be deplored. I am sure we should all be glad if in specifying for machinery it could be done upon the basis of the best possible machine rather than trying to get all the manufacturers in one fixed groove where they can produce a standard article and everybody can compete with everybody else. I should advocate the principle of machinery being purchased upon the basis of excellence rather than upon that of lowest price.

In conclusion, I would say that one very pleasing thing shown in the paper is that Mr. Rider has obtained such a fair coal contract. I think it is one of the most cheerful signs with regard to municipal trading that I have seen, that a contract has been made in which the contractor is absolutely on an equality with the people who are buying from him.

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Mr. ROGER T. SMITH: The author in his paper speaks of the change of site from Camberwell to Greenwich, and justifies this change for two reasons: first, that his coal is cheaper, and secondly, that he avoids annoyance to the neighbourhood from the presence of cooling towers. Dealing with the last reason first, I should like to ask the author if he considers that that in itself would be sufficient to have justified the change; and then I wish to discuss the question of cheap coal. On page 237 it is stated: "The whole of the coal (some 150,000 tons per annum) would have to be brought by rail, and the ashes removed by the same means. Taking the difference in freight between rail-borne and water-borne coal as 3s. per ton, the extra carriage alone would be £22,500 per annum over a river site." It is the alleged extra cost of 3s. per ton of rail-borne over sea-borne coal on which I join issue with the author. For boiler furnaces using chain-grate stokers at present bituminous coal is necessary—that is to say, a coal having at least 25 per cent. of volatile matter. The natural bituminous coalfield for generating stations south of the Thames is, in my view, the Midland coalfield of Staffordshire, Warwickshire, and South Derbyshire. All sea-borne coal is partly rail-borne, and its cheap carriage must largely depend upon the relative distance it is carried by rail and by sea. If it is partly carried by rail, it must be handled at least twice and sometimes three times before it reaches the bunkers. For a generating station like Greenwich on the Thames it is possible at the present time to get coal from such a port as Goole in South Yorkshire that fulfils the conditions required for chain-grate stokers, and as far as I am aware the only other possible ports are in the Firth of Forth, from which the author at present gets his coal. In the admirable specification for coal, which has been already referred to, the author states that his coal when dry gives 12,500 B.Th.U. per lb., and one gathers from its success from the contractor's point of view that this value is nearly always equalled, if not exceeded. On page 272 it is stated that for last year's results part of the price was 14s. 5d. a ton, and part of the price was 11s. a ton delivered into the outside bunkers. Mr. Smith.

Mr. RIDER: No: in ship, alongside. Mr. Rider.

Mr. ROGER SMITH: That involves a slight extra cost, which is of little importance. The freight to an ordinary trader from a place like Nuneaton in the Midland district—I take Nuneaton because it is about the centre of that district—to the existing coal depôt on the South-Eastern and Chatham Railway, just by the proposed Camberwell site, is 6s. 6d. per ton. For large quantities that price would be reduced to 6s. When coal was dear last year, at my station at Park Royal I obtained coal, of a calorific value when dry of 13,250 B.Th.U., at 7s. 10½d. delivered into wagons at the pit near Nuneaton. That coal could therefore have been delivered over outside bunkers at Camberwell for 14s. 4½d., if no special rate was given for a large quantity, and for 13s. 10½d. at a special rate. That cost probably corresponds with Mr. Rider's figure of 14s. 5d. When coal was cheap at the end of 1908 I obtained exactly the same coal at Park Royal at a cost of 5s. 4½d. per Mr. Smith.

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Mr. Smith. ton delivered into wagons at the pit. That could have been delivered over bunkers at Camberwell, taking the special rate at 6s. per ton, at 11s. 4½d., corresponding to Mr. Rider's price of 11s. I think it is therefore quite clear that coal having a heating value about 750 B.Th.U. higher than the coal that is now being delivered at Greenwich could have been delivered by rail over bunkers at Camberwell from the Midlands for the same price that Mr. Rider is now getting it alongside, and not for 3s. more, which he suggests would be necessary. I feel this is a matter of some importance, because it seems to be considered by many people as a fact that if you want cheap coal you must have the coal sea borne, and have a station by a river. I hope I have shown that that need not always be the case. But this is not all. If I read the paper aright, the author suggests that it is a disadvantage that the ashes should have to be removed by rail. One can judge this best by actual results. Park Royal is a station designed by Messrs. Kennedy & Jenkin on very much the same lines, as far as the method of delivery of coal and its general coaling facilities are concerned, as the original station designed for Camberwell. At Park Royal I am using to-day Midland coal having an average calorific value of 13,250 B.Th.U., which is costing 5s. 4½d. per ton delivered into wagons at the pit. A portion of that freight is over my own railway, but that makes no difference—I am charged 5s. 3d. per ton for freight; anybody could get it at 5s. 6d., and anybody who requires a considerable quantity could get it at 5s. 3d. The cost of delivering from alongside into the outside bunkers, I believe I am right in saying, is about a penny per ton at Greenwich.

Mr. Rider. Mr. RIDER: Twopence a ton into the inside bunkers.

Mr. Smith. Mr. ROGER SMITH: It may perhaps be a halfpenny more or less. The cost, taken over the whole of last year, of delivering each ton of coal from the wagons into the outside bunkers at Park Royal was $\frac{1}{3\frac{1}{0}}$ of a penny.* The ashes are conveyed into a hopper, from whence they shoot into wagons and are hauled direct to brickfields, where they fetch a price of a little more than 1s. a ton. This price is just sufficient to pay all the capital and maintenance charges on the whole of the special coal and ash hopper wagons employed in the Park Royal service, and leave a trifle over. Such a result can only be obtained if ashes can be delivered by rail, unless there happened by chance to be a sale for ashes so close to the station that the cost of carting is insignificant, while if they have to be barged and then unloaded this would probably more than equal the value of the ashes. I hope I have shown that a Midland coal which is wholly rail-borne costs at Park Royal to-day 10s. 7½d. per ton delivered over bunkers, including the handling of all the ashes, and all capital and maintenance charges on the coal and ash wagons, as against 11s. at Greenwich. The calorific value of the Park Royal coal is just a little better than the calorific value of the Greenwich

* In the discussion this was wrongly stated to be $\frac{1}{4\frac{1}{0}}$ of a penny. This is the cost not per ton, but per kilowatt-hour, delivered to sub-stations, of delivering coal from wagons into the inside bunkers and removing the ashes into wagons.

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coal, but comparing coal costs it must be remembered that Mr. Rider's sets are 3,500 k.w. each, while those at Park Royal are only 750 k.w. The author's maximum load last year was 16,000 k.w.; at Park Royal it was 4,000 k.w. The author's annual output was 66,000,000 k.w.-hours; at Park Royal the output was 14,000,000 k.w.-hours. The Greenwich costs for coal during 1908 are 0·2327d. per kilowatt-hour, delivered to sub-stations. There is an objection to giving the costs at Park Royal for the whole of last year because the engines were still in the hands of the contractors, and everybody knows that an engine is not much good until it is paid for. But during the last two months of this present year, during which coal was wholly 10s. 7½d. per ton over bunkers, my coal and ashes costs were 0·1959d. per kilowatt-hour generated, and 0·2181d. per kilowatt-hour delivered to sub-stations, with a machine load factor of 79 per cent. I do not wish to put forward these particular figures for the last two months in comparison with Mr. Rider's figures for the whole of last year. Probably Mr. Rider's costs for the same two months may be appreciably less than they were for the average of last year. The point I wish to make is that for a station used for both lighting and traction purposes, containing sets of small size and employing cooling towers, the coal costs with rail-borne coal are quite equal to coal costs with sea-borne coal in a much larger riverside station with an equal or better machine load factor. Since actual results have been quoted it may be as well to point out that in any comparison between a cooling-tower station and a riverside station, the former's coal costs ought to be debited with the cost of the make-up circulating water. Owing to the failure of the well sunk at Park Royal water costs are for the present exceptionally high, and the cost per kilowatt-hour of the make-up cooling water for the two last months has been 0·006d. The cost of circulating over cooling towers is probably rather less than the cost of pumping from the Thames through the revolving screen, but assuming the pumping costs to be the same, the Park Royal comparative coal cost should be 0·2241d. delivered to sub-stations, instead of 0·2181d. exclusive of make-up water. Mr. Smith.

Mr. C. P. SPARKS: I think London is to be congratulated on one fact brought out in the paper. Mr. Rider does not actually tell us so in so many words, but I gather from the paper that the whole of this great plant is of British manufacture. It is not every corporation in England that is so public-spirited as the London County Council, and I hope the example set to English municipalities will be followed, because it is clear from the figures before us that London has not suffered by placing the contracts in this country. On the contrary, I believe this is one of the finest examples of power station work in the world, carried out at the same time for a reasonable expenditure, having regard to the class of plant erected at Greenwich. I agree entirely with the remarks of Mr. Ferranti on the subject of the site of this power station. There are few men who have the opportunity of selecting the site of a power station for such a great undertaking, and I feel the author is one of the few men coming on the scenes, not at the Mr. Sparks.

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Mr. Sparks. very inception of the scheme, but at a late period, who would have been bold enough to have gone in for this river site. Despite the remarks of the previous speaker, I feel that Mr. Rider has hall-marked himself as an engineer in selecting this down-river site at Greenwich, as the ultimate size of the tramway undertaking would not warrant the supply being subdivided between two stations. The paper is very ample, but there are one or two points as to which I should like further information. First, with regard to the choice of a system, we have here a 25-cycle system and a pressure of about 6,600 volts. Personally, I should have thought for this large area a higher pressure than 6,600 volts would have been economical. There may have been good reasons that are not before me for not adopting a higher pressure, but I should like to ask the author what justification he has for adopting this comparatively low pressure. In my opinion, London, large as it is, is bound to expand, and the London tramway system with it. Next, I should like to mention the coal clause which is given on page 241. I think that is a very admirable and fair clause to both parties, and I understand it has worked satisfactorily. Possibly one part of the clause has not come into operation, namely Section (*d*): "The Council, however, has the right to reject the whole cargo if the moisture exceed 13 per cent. by weight." In working clauses of this kind it is always a difficult thing to reject, because you cannot test the coal until it has been unloaded. The demurrage on a consignment is heavy, and it is necessary to begin unloading promptly. It appears that for penal clauses to be really effective a money compensation should be given, because power to reject, once the coal is in the bunker, is nearly impossible. On page 257 the author refers to turbines. "Turbines have been adopted for the remainder of the station, but not for any reason connected with the performance of the reciprocating sets. Conditions of output, space, and price were the only determining factors." I think there are other determining factors, and in another year perhaps the author will tell us that coal, labour, oil, and repairs were really determining factors in addition to those given in the paper.

With regard to the reciprocating plant, I think 94 revolutions is too high a speed for Corliss valve gear with units of this size, and will wear out quickly. Having had some experience with turbines, it is my opinion, contrary to that of another speaker, that the turbines will be there long after the reciprocating plants have been parted with.

Turning to electrical matters, the author refers to reverse-current relays and the earthing of the system. With regard to the first, Mr. Rider only gives a suggestion, but I must say I am in hearty agreement with him. The question of reverse-power relays is one of the most difficult problems that central station engineers have to deal with. Mr. Rider says on page 260, "Reverse-current relays are fitted on the generator circuits and time-limit overload relays on the feeder circuits. Experience with the reverse relays has almost converted the author to the opinion that the generators should have no tripping relays of any kind whatever."

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Mr. RIDER: May I say that the word "almost" should now be "quite." Mr. Rider.

Mr. SPARKS: I am in hearty agreement with the author of the paper on that point. With regard to the earthing system, I think we are very much indebted to the author for pointing out a solution to a most difficult problem. My whole experience has been in working with systems connected to earth. When a number of 3-phase generators are worked in parallel the difficulty of earthing the system is great, and I think the author is the first person to point out the proper solution of the difficulty. I should like some further information as to the diversity factor given on page 291. The author does not tell us how it is measured, which is all-important. He simply says, "The diversity factor of the sub-stations, *i.e.*, the ratio of the sum of the maximum loads on the individual sub-stations to the maximum load on the generating station, in any one day is about 1·25 in." Is that the hourly demand in units at the sub-station, or is it only the instantaneous demand? If it is the latter, it is easily met by the overload capacity of the converting machinery; while small momentary fluctuations at a number of sub-stations would not affect the power station. Mr. Sparks.

A direct comparison with the costs of other undertakings would be possible if the author would give some additional information as to the capital cost on mains and sub-stations, together with the cost of working sub-stations and efficiency of conversion. Tables IV. and V. give full information as to the capital and working costs of the station, but the costs here set out are not comparable with those of other undertakings, where the costs per unit include costs of distribution and conversion. As this information would considerably add to the value of the paper, I hope the author will be able to give it in his reply.

Mr. G. W. PARTRIDGE: I am very glad that Mr. Sparks agrees with me in the great objection to reverse-current relays on generators, and also to hear that Mr. Rider is himself now "quite converted" to the fact that they are absolutely wrong. When I have been at other generating stations I have nearly always found that these relays are tied up with string or wedged up with pieces of wood so that they cannot come into operation. It has always been my contention that the control of a generator should be in the hands of the switchman only. Mr. Partridge.

As regards the earth current from the neutral point of the star winding of the generators, referred to on page 261, I am rather inclined to think that this has something to do with the particular design of generator, and does not always exist. There are a great many generating stations, 3-phase, 25, and 33 periods, which have their neutral points all connected up solid. I have four 3-phase machines at Deptford, and we have no trouble at all in this particular direction. I should like to know what the author's experience is with his turbine sets—*i.e.*, if he gets the same flow of current from the neutral points of these generators as with the reciprocating plant. On page 265 I notice the author says he drives the centrifugal pumps in connection with the

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Mr. Partridge.

condensing scheme by means of 3-phase motors; I cannot help thinking that this is a mistake and very uneconomical. I think that these centrifugal pumps should be driven with direct-current motors, so that the speed of these pumps may be altered if required. Owing to the use of commutation poles direct-current motors with a range of speed of three to one may be purchased and run at high efficiency at all speeds. I cannot therefore help thinking that the use of 3-phase motors for driving these pumps must cause a great amount of loss in the system. There is another important objection to these 3-phase motors, namely, that in the case of loss of steam or sudden overloads on the station which reduce the speed of the generators, the periodicity and speed of the pumps will fall at the time the author wants most of his circulating water and the best vacuum. When turbines are in use the author will find this trouble even more exaggerated, owing to the very high vacuum required for this type of plant.

The rush of current when switching on induction motors, which the author refers to on page 274, is an old trouble, and one of which I have, unfortunately, a considerable amount of experience. In the old days when we switched the Ferranti transformers on to the 10,000-volt system we had these rushes of current and failures at the ends of the coils in exactly the same way that Mr. Rider has pointed out. We got over the trouble in the case of the converters by always switching on the low-tension coil of the transformer first; and I came to the conclusion that these rushes of current depended more or less on the way in which the iron of the transformer had been left magnetised the last time it had been switched off, and at what particular point of the phase the connection was again made, as the rush of current used to vary considerably. Some four or five years ago we had exactly the same experience in switching some 250-k.w. induction motors to our lighting system. The whole difficulty was got over by the use of water resistances. We tried induction coils but found them unsatisfactory. Since then I am given to understand that several makers use these water resistances in connection with their apparatus. I can mention two or three firms who have got out a standard design for this particular apparatus, and I am rather surprised that Mr. Rider's contractors when they supplied these induction motors did not mention the trouble to him, or at least offer to supply some sort of resistances for preventing these disturbances and failures of insulation of which he complains.

I should also like to ask why the author has not used more rotary converters instead of using so many motor-generators, as his periodicity is such a low one. It would, in my opinion, have saved a considerable amount of capital outlay in the first instance, and improved the efficiency of the system. There are many large railway companies in London who are using rotary converters with satisfactory results. Moreover, I believe rotaries are used in many places not only for power but also for lighting systems.

Mr. Rider has been kind enough to mention my name in the paper. I can only say it has given me very great pleasure to have been of any

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assistance to him in connection with the undertaking, and I must congratulate the author on his most excellent paper and the interesting results he has given us. Mr. Partridge.

Mr. ROBERT HAMMOND: One of the most important pieces of work of our Institution is to include in the *Journal* from time to time descriptions of the foremost specimens of engineering work, which years hence will be read with the greatest pleasure. From this point of view Mr. Rider's paper is particularly opportune, because it gives us a description of works which have been described as the passing of the reciprocating engine. We are all having this experience. I was busy in Leeds last week in testing duplicate turbine sets of those which Mr. Rider has at Greenwich. I hope when the author has tested these two new sets he will favour this Institution with the records. Apart from that, however, the paper has one or two features that appeal to me, and I am sure they appeal to you. One of the most important sentences of the paper is, "A reputation for absolute continuity of supply is worth a great many pounds of coal per annum." There, I think, we have the true spirit of the engineer. We want absolute continuity of supply, and that, I believe, has been secured at Greenwich. Mr. Hammond.

Possibly the author in his reply will tell us whether they have ever broken down at Greenwich, and if so, why; whether he has been able to fully attain what he set himself to attain. But the engineer has another point to bear in mind. Not only does he want to secure absolute continuity of electrical supply, but his lords and masters want him to obtain it at the lowest possible cost. That invests the table on page 271 of the paper with the greatest interest, and it is a point on that that causes me to speak when I had thought that, as I have done so much talking at this Institution, I would leave it to others. But the remarks of Mr. Roger Smith cause me to break the silence which I had decided to adopt to-night. Most of the gentlemen present, including Mr. Roger Smith, because he was in and out of the Committee-rooms, know that last year, the year before, and the year before that, it was my lot as a colleague of the author's to uphold the principle of riverside generating stations. Many of you remember that we were for thirty-one days before Lord Cromer's Committee, and the burden of the whole argument was that riverside stations were absolutely necessary to obtain cheap generation; and yet we have our friend, Mr. Roger Smith, getting up and saying that, on the whole, Mr. Rider made a great mistake when he forsook Camberwell and went to Greenwich.

There is one point to which I would like to draw Mr. Roger Smith's attention. It is that he has contented himself by describing how cheaply coal could be obtained at certain times at certain places, but he did not enter into the condensing part of the problem at all. We do not want these generating stations in the centre of London. Surely stations must be placed where condensation can be carried out cheaply and efficiently. A plea for a station at Camberwell of 16,000 k.w., growing gradually to 30,000 k.w., is certainly not one that we can support at this Institution. If there be one thing that the last few years have

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Mr. Hammond.

taught us, it is that stations situated on a river site, with cheap coal and water available, afford the cheapest possible methods of generating electricity. With regard to that problem, I believe I am right in saying that on the Rand (to go a long way off) a Company under the name of the Victoria Falls Company has decided to lay down their generating works some 39 miles from Johannesburg. That Victoria Falls Company is developing on the lines of laying down steam-driven stations. The output is expected to reach 500,000,000 units per annum. The prospectus for the extensions will come out to-morrow morning. I am not here to advertise it, or persuade anybody to put their money into it; but it will be found that, in the endeavour to hit upon the proper site, they have decided to lay down the works some 39 miles from Johannesburg, at Vereeniging, where coal and water are available almost side by side at a riverside station. I hope what Mr. Roger Smith has said will not be taken throughout the world as representing the opinions of this Institution—that we would rather, on the whole, have coal brought by rail and delivered into the heart of London. If Mr. Roger Smith is right, that we do not want river-borne coal, and that we are to put our stations up in inland places and deliver the coal to them there, how is it that a glance through the list in the *Electrical Times* shows that the places where river-borne coal is used have an advantage over the others? Take Hackney, the cheapest station, as it happens, in London. Some of my friends smile, and think that Hackney owes the fact that it has cheap coal to the circumstance that I put up the works. Let me tell them that Hackney's low coal cost is due to a combination of circumstances, and one of the principal is that it uses river-borne coal. I would also like to draw attention to two other points. I draw your attention to the excellent results which the author has achieved, as set out on page 271 of his paper, namely, 0·3311d. per unit delivered to sub-stations, equal to about 0·3, or possibly a little more than 0·3, at the generating station. If you search the records of the country, and if you search, as Mr. Mordey, the President, would say, the records of Germany, you will find no place where electricity on that output and load factor is being generated so cheaply. My last point is this, and it is a point that came up in the excellent speech of our friend Mr. Bailey. To me, as one of the older Members of the Institution, and viewing Mr. Bailey, from his alertness and freshness, as one of the younger ones, I must say it was a great pleasure to me to hear him make his speech. But he made one marvellous statement. He said that the reason for the author's low costs was that he had such a splendid revenue, and Mr. Bailey actually worked out that Mr. Rider's revenue was about £85 sterling per kilowatt. £85 per kilowatt! Multiply it up. 16,000 k.w. multiplied by £85 comes to over £1,300,000. Has Mr. Rider a revenue like that? He has a revenue very much like Mr. Bailey's revenue. Mr. Bailey's revenue is £267,159 sterling on a maximum load of 23,200 k.w.; Mr. Rider's revenue is about £200,000 on a total output of about 16,000 k.w. Mr. Bailey's revenue is about £11 10s. per kilowatt; the author's is about £12 8s. How Mr. Bailey ever got this £85

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into his mind I do not know, unless upon the supposition that he has taken all the pennies that the people pay on the tramways! The author's revenue is what he is paid for the electricity delivered to the sub-stations or to the tramway motors. Mr. Bailey's revenue is for the electricity delivered to a newspaper office, but he does not consider the pennies obtained from the *Standard* and other newspapers as part of his revenue. If he does they do not figure in his balance-sheet. Mr. Hammond.

I cannot speak to-night on behalf of the Institution, but I am sure I shall be voicing the feeling of those present at this meeting when I say that we are all of us proud of this piece of work, and we are delighted with the paper as a record. I am sure we all stand by Mr. Rider, and consider that he was right in moving from the green fields of Camberwell to the pleasant seaside resort of Greenwich.

Mr. H. E. O'BRIEN: I should like to join in the general chorus of congratulation to the author on his excellent and interesting paper. I have only one or two criticisms to make, but a great many questions to ask. With regard to the coal specification, I do not know exactly what the size of Mr. Rider's coal is, but 10 per cent. of moisture appears a rather high figure. It seems to me to give the contractors rather more latitude than one would expect. Mr. O'Brien.

Mr. RIDER: It is washed coal, remember. That is the reason the moisture is high. Mr. Rider.

Mr. O'BRIEN: I was comparing it with washed coal. The Lancashire and Yorkshire Railway Company use washed coal at the Formby station, and tests made there do not show that we ever obtain 10 per cent. moisture figure as an average for the year. With regard to the boiler plant, the total evaporative capacity of the author's boilers is 828,000 lbs. per hour. The maximum working load that the author expects to obtain is 30,000 k.w. Adding about 25 per cent. to the full-load steam consumption of his engines, which is a very liberal allowance for auxiliaries, etc., under full-load conditions, the steam consumption will amount to 600,000 lbs. per hour. It would therefore appear that, without forcing the boilers in any way, 25 per cent. of them could be laid off for spares and repairs at the maximum load. Mr. O'Brien.

Mr. RIDER: That is the idea—to have 25 per cent. Mr. Rider.

Mr. O'BRIEN: Considering the extent to which a water-tube boiler can be forced if required, it seems to me excessive to have 25 per cent. spares in an undertaking of that capacity. I would like to know why the bunker capacity was fixed at 11,600 tons; this is equal to four weeks' supply at the eventual full load of the station; with rail-borne coal such a reserve would be necessary, but with sea-borne coal the bunker capacity seems unnecessarily large. Fewer boilers and smaller coal storage room would have reduced the capital cost of the boiler house very considerably. The author states that the gases leave the boilers at 620° F. and enter the economisers at 500° F. This seems a large drop of temperature, and it would be interesting to know the cause of it. I notice the author states that the engines were tested with steam at about 450°, but the superheaters give 150° superheat. I Mr. O'Brien.

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Mr. O'Brien. would like to know whether he is working with the full superheat on the Corliss engines, and what a difference there is in steam consumption if the receiver reheaters are not in use. At Formby we are now working with steam at a temperature of about 510°, and that seems to be the extreme limit of the ordinary Corliss valve gear; that is to say, the valves tend sometimes to groan, and without the use of special lubricant the engines do not run quite satisfactorily as regards the valves. At Formby we have no separators on the steam pipe—at least there is a separator, but it is a very small one—and I have been quite unable to detect any traces of moisture in the steam coming to the engines. It would therefore seem that with steam at 150° superheat separators are an unnecessary expense, and I would like to know how much water Mr. Rider finds is collected in the separators. I thoroughly agree with his remarks as to the advisability of having comparatively large clearances with turbines if they are necessary to secure reliability, but I think it would be very interesting if the author would tell us what his clearances are and what percentage of the diameter they represent, and whether they have been measured hot or cold. I have seen many cold measurements of clearances in turbines, but I do not know of any figures as to what the clearances are with the turbines when running at their full temperature. I would like to know also whether the author has finally adopted the impulse turbine because he hopes to obtain more reliability due to the large radial clearances of that type, and whether he is not afraid of possible loss of efficiency due to blade erosion, and whether in ordering turbines he calls for tests after, say, two years' working.

I have been very interested in what the author said about cross currents between the generators. At Formby we have four 1,500-k.w. 25-cycle alternators running in parallel. I have put ammeters in the neutral, and as Mr. Partridge also stated, I have not found any cross currents between those engines, but when a 4,000-k.w. turbine is put in parallel with the reciprocators then there is a considerable cross current, of about 50 amperes working at 7,500 volts. That has not caused any trouble in working. The generator neutrals are all connected together and to earth without any resistances. I notice that the author's feeders are fitted with time-limit relays. We have heard a just condemnation of the reverse-current relays on the generators, and I would like to know what is to be said for the time-limit relay on feeders. The time-limit relay seems to me to be in its place on overhead bare high-tension feeders, where there is hope of an arc burning itself out and clearing itself, but with such cable systems as we have in this country anything that happens on the high-tension system usually results in a dead short, and the sooner it is cleared off the better. In many stations that I have been in I find that, under these circumstances, the time part of the time-limit relay is out of operation. Does the author find that the spark-gaps on the feeders serve any useful purpose—have they ever been observed to discharge?

Finally, I would again express my admiration of the systematic and

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thorough manner in which the whole undertaking has been planned and executed. Mr. O'Brien.

Mr. H. W. CLOTHIER: I would like to say a few words on the subject of protection. The author's opinion about reverse-current relays for generator protection is not quite definite in the paper, but I understand from the remark he has just made that he is now convinced that reverse-current relays are a mistake for generator protection. Is he quite correct in suggesting no tripping relays of any kind whatever for the protection of alternators? I am prepared to agree with him that it is better to have none than to use reverse-current relays, but at the same time I think we must have some automatic protection. I admit that often a short between phases or even an earth on a generator winding will gradually develop smoke, and so give the switchboard attendant time to pull the machine out by hand before anything serious has happened to the continuity of supply, but Mr. Clothier.

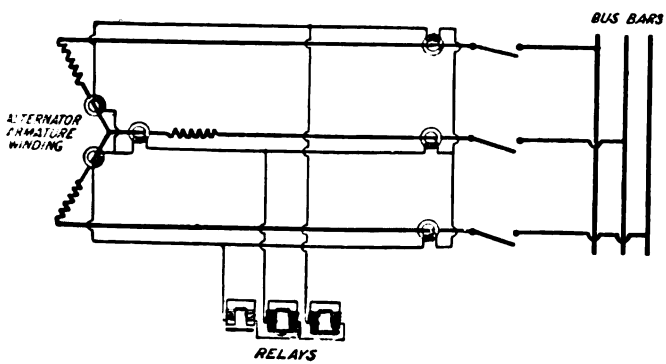

FIG. A.—Balanced System of Generator Protection (Merz-Price Patent).

occasionally faults occur which cannot be dealt with so easily. Emergencies happen of such a nature as to call for too much from the switchboard attendant. For example, I have seen a turbo-alternator which simply burst and flew into hundreds of pieces. Such an accident is fortunately very uncommon, but it may occur in any of our generating stations, and I suggest that automatic protection would be more efficient in dealing with the exigencies of the case than a switchboard attendant.

The solution of this problem is to use the balanced system of protection. This system at present has not been very largely applied to generator protection, although it is a feasible scheme which can be relied upon to cut out a faulty generator by relays acting instantaneously. Thus a serious fault in a power station can be cleared without upsetting any synchronous plant on the system.

Fig. A illustrates the connections as required for the protection of 3-phase star-wound alternator. It will be seen that there are six transformers, the secondaries of which are in electrical balance during

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Mr. Clothier.

normal conditions. The balance is also maintained for heavy overloads occasioned by faults external to the generators, but in the event of a fault occurring anywhere between the current transformers the equilibrium is destroyed and current flows through the electro-magnets of the relays, which trip out the switch.

Reverting to the construction of the switchgear, the author's scheme is as sketched—Fig. B. It consists of many ironclad parts (those marked A), jointly connected with isolating switches, busbars, etc., through several lengths of cables. Let us see if it is possible to reconstruct the arrangement. The author has started with certain ironclad parts, and I would like to show how the system could be simplified by carrying the principle which is so inaugurated through-

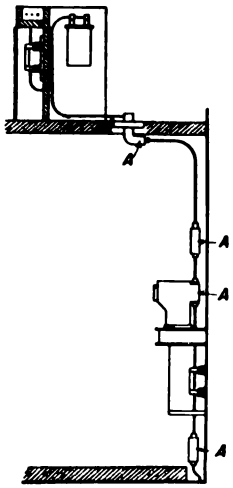

FIG. B.—Mr. Rider's Arrangement.

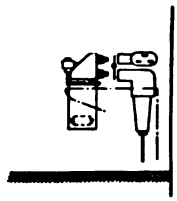

FIG. C.—Ironclad Switchgear contains same apparatus with greater security.

out. It would be necessary to put a slightly different shaped casting to contain the current transformers, the cable dividing box being attached directly thereto. The busbars would also be enclosed in an iron chamber run in solid with compound and placed directly above the transformer chamber. The whole would be carried on a frame, and a switch in the form of a carriage would plug in and thus complete the circuit between the busbars and the current transformers. This rearrangement is illustrated on Fig. C. We have now got all the provisions for isolating that are on the author's scheme Further, we still have his idea, which is a good one, of having the transformers enclosed in a cast-iron chamber, but we have also enclosed everything else in cast iron, including the busbars, and we have obtained a switchgear which occupies much less space (without impairing the insulation or reducing clearances), and is altogether

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a safer arrangement. We have no concrete partitions, no brickwork, no straggling cables in between parts. We have done away with the isolating switches, which I contend are a grave source of danger. Mr. Clothier.

In the brickwork or concrete-cell type of switchgear construction it is serious to contemplate that a man may meet his death merely by entering the wrong panel. Such fatalities have occurred, and the danger is eliminated by a properly developed ironclad construction. This type is now extensively used, and will, I believe, in some form or other, prove to be the switchgear of the future.

Mr. J. F. C. SNELL: The author is too old a friend of mine for me to attempt a laudation of this monumental work of his, but there are one or two salient points which must have struck all of us who have read the paper and seen the admirable lantern slides to-night. The first is that, although this station was commenced prior to 1901—more than eight years ago—there is no evidence of patchwork in the whole of the design, neither in the power house, in the transmission system, nor in any of the sub-stations. In other words, it has been a well-thought-out scheme from the beginning, and throughout the whole of those eight years it has gradually unfolded and developed. Those of us who have to design growing stations know what a great difficulty it is to be able to foresee the future, and to design our stations upon regular lines. I think this system of the London County Council which the author has designed and carried out bears pre-eminently that mark of being well thought out. Then with regard to the question of design, I have been struck by the extreme simplicity of the whole system, whether one looks at the pipe-work design or at the switchgear. Despite what Mr. Clothier has shown us in that connection, there is an element of real simplicity throughout the whole of the station and of the sub-stations. Simplicity is the hall-mark of good design. At this late hour I must not speak for more than a few minutes. Many of my points have been dealt with by other speakers, and I shall therefore content myself with asking one or two further questions, which no doubt the author will be able to answer in his reply. One is, "Why did he put the switch cells on the third gallery of the switchboard? Why could they not have been put in the gallery underneath the operating boards?" I venture to suggest that had that been done a very great length of cable would have been saved without any sacrifice of simplicity or power of control. My second point is that on page 273 arrangements are made for 33 per cent. of spare plant in motor-generators. Surely that is an excessive amount. I know that Mr. Rider always likes to be on the safe side, but I suggest that in the sub-stations, which appear mainly set out to accommodate six sets (five working and one spare)—in other words, 20 per cent. spare—there would have been a considerable saving in capital expenditure, and at the same time a sufficient insurance against breakdown in one spare set plus the overload capacities of the five other motor-generators. Mr. Partridge has already asked one question which was in my mind, and that is, Why did the author not adopt rotary converters? Why did he Mr. Snell.

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Mr. Snell.

adopt induction motor-generators and synchronous motor-generators? I suggest to him that not only would he have saved capital expenditure, as Mr. Partridge has already pointed out, but he would have saved to some extent that initial shock of switching in to which he refers; but more particularly he would have saved in efficiency. Taking the average efficiency of his motor-generators at, let us say, 82 per cent., which I think is a fair figure, I am sure he will admit that the static transformer and rotary converter on the same average load would give a 10 per cent. greater efficiency. If one looks at the number of units delivered to sub-stations, which are in the neighbourhood of 57 million units, a very simple calculation shows that practically 6 million units would be saved, representing some 7,000 tons of coal, or at the average price given by the author, £4,200 per annum. That is a very serious figure. No doubt the author will be able to give us admirable reasons for adopting motor-generators, but in any new design which one had to undertake it seems to me that rotary converters, especially at the low periodicity very properly adopted in this case, would give better economical results than the motor-generators which he has installed. It is rather interesting to notice in Table V., on page 271, that the actual cost with reciprocating engines, 0·33d. per unit delivered to sub-stations, is only 23 per cent. in excess of the figure which Mr. Rider and others of us estimated to be the cost of the lately proposed power station at Barking for the supply of the County of London. Although that station was to have given an output nearly four times the present output at Greenwich, the author is already within 23 per cent. of the very-much-laughed-at figures which we put before the Lords and Commons Committees. I think that shows that our figures were not so very far wrong. From statistics given in the paper on page 293, the car mileage is given as 25,591,028 miles; the units metered—not the units delivered to sub-stations, I take it, but the units after conversion—were 57,000,000, and the units per car-mile are 2·24—the highest figure in the three kingdoms. There must be a reason for that. Of course I know that the County Council cars are heavy and very large, and that a number of them have magnetic brakes. All that must mean an expenditure of energy; but on the Glasgow system, also a 3-phase system with sub-stations, but with rotary converters in most cases and probably with smaller cars, the units per car-mile are only 1·25, a little more than half of the expenditure of energy in the County Council system. I should like to ask what is the reason for that very large expenditure per car-mile, because it seems to me, compared with what the other systems in the country are doing, to be, if I may use the expression, rather an outrageous figure. Finally, may I ask if the author will give us the power factor of the whole of his system? He has given us very many admirable statistics, but that one item of power factor is missing, and it would be of very great use to us if we could have that figure added to the statistics in the paper.

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ADJOURNED DISCUSSION, APRIL 22, 1909.

Mr. W. H. PATCHELL: Some of us are interested in this paper entirely from the point of view of heavy engineering; others because of the large field covered by the paper; others, again, possibly because they feel that this scheme comes out of their own pockets, and are, therefore, interested in it. Mr. Rider has put before us a most instructive table of the clauses which he has called for in the coal contract. The point in it that struck me most was that there is no mention of ash. Possibly he only intends this contract to apply to a very restricted class of coal, in which case the heat value should cover the ash, because with coal of one particular kind the heat value could not vary widely if the ash varied; but I think the terms would have to be altered to make them of general application and value. Dealing with the question of coal, I notice that Mr. Rider has gone in for washed nuts, and that brings up the question of the chain-grate stoker. I remember some years ago burning washed nuts, from which I got very high value from £1. Shortly afterwards Lot's Road was equipped with chain-grate stokers; Mr. Rider followed with more chain-grate stokers, and washed nuts went up to a price at which I could not follow them. I therefore had to turn my attention to other classes of coal. I think it a great advantage to use the same class of fuel throughout a station, but to have a type of plant which so very much restricts the type of fuel which can be burnt is a disadvantage, unless the power company is also a colliery owner, and produces its own fuel. With regard to the question of heating surface, referred to on page 244, the author gives in Table II. the heating surface of each boiler. He states that the superheater is included in the boiler, does the figure of 3,320 sq. ft. include the heating surface of the superheater? If not, will he tell us what the heating surface is? The size of the boiler seems very small in proportion to the size of the power station. When I had the pleasure of describing the Bow plant of the Charing Cross Company before the Institution some years ago* I showed some boilers which were normally rated at 66,000 lbs., and evaporated 100,000 lbs. of water per hour. Some people thought those boilers were too large, but I do not think they are if the size of the works be taken into account. In a much smaller installation of 5,000 k.w., which I have lately designed, I have put in some boilers which are normally rated at 30,000 lbs. an hour, and have found it a very convenient and economical size to use. On page 244 Mr. Rider gives us an interesting test of one of his boilers. The boiler has 3,320 sq. ft. of heating surface, and its efficiency was found to be 79·49 per cent. The boilers that I have just referred to have 6,209 sq. ft. of heating surface. They are Stirling boilers, with McPhail superheaters of 800 sq. ft. of heating surface, made up as an integral part of the boiler. The test on those boilers with dry fuel came out at 80·92 per cent.—that is, boiler and superheater combined without an economiser,

Mr. Patchell.

* *Journal of the Institution of Electrical Engineers*, vol. 36, p. 72, 1906.

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Mr. Patchell.

so that the figures are really quite as close to the author's figures as could be expected. I do not claim there is any greater thermal efficiency in the larger boiler, but I do claim greater convenience in handling, and a very great efficiency and saving in the cost of buildings and the cost of land. As the author was using double-compound engines, the space taken by the engines gave him plenty of room to put his boilers down alongside; but where he is considering a turbine proposition the space occupied by the boilers is much more important. The larger boiler occupying less ground space scores considerably.

The question of the water level in London is a very interesting one, and it is becoming more important in view of the number of people who are putting down their own wells. I am much struck by the statement on page 247 that the well will deliver the water practically up to the ground level, 5 ft. below the top of the tube. Could Mr. Rider give us a reference to show the top of the tube level as compared with Ordnance Datum? I have operated deep well pumps on that side of the river and on the other side of the river at West Ham, and the water level relatively is very much lower than the author describes it. I have heard that at Greenwich the water stands higher than in London, but with all the pumping that is going on I should have thought it would have fallen lower than the author indicates. Water finds its level, but it takes time to do so. Then I should like to ask, are the Kennedy water meters on the suction or delivery side of the pump? There is a good deal of difference in the wear and tear of the meter, and also the accuracy with which it will read, depending on whether it is placed on the suction or delivery side. The steam separator has a page all to itself. Is that justifiable? In a well laid out plant with steam superheaters, why does he want so much steam separation? I congratulate him on the design, but I should like to suggest to him that he might have applied to this steam separator an indicator, the excursion of which would have told him the amount of superheat at a given steam pressure. The steam separator for other reasons seems to be rather wasted on that plant. On the generating plant there is rather a striking difference in the rating of the reciprocating sets and the turbo-alternators. I note that he buys his reciprocating sets with a power factor of 0·94, but the turbo-generator sets have a power factor of 0·85. Why the difference? More important still, would he tell us what is the power factor on the plant? As Mr. Rider tells us, they are all induction motor-generators, but what is the power factor at full and at half-load, and what can he keep the station power factor up to day by day? The question of piston rings has previously given trouble, and I notice the author has had a taste of it. I should not have expected that his piston rings would have given out before his Corliss valves did, and I am interested to know if he has also had the latter trouble. He has not mentioned it. Mr. Rider has been exceedingly candid and honest in the paper, and I infer from this that he has had no trouble with his Corliss valves, but only with his piston rings. I always shy from

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Mr. Patchell.

Corliss engines on superheat on account of the valves rather than the piston rings. The design of the engines is very interesting. I have seen the Manhattan engines where they were born, and I was struck when I first heard from the author that he was reversing the Manhattan method. He has put the low-pressure cylinders horizontal and the high-pressure cylinders vertical, whereas in the Manhattan engine it is just the opposite. Mr. Rider claims better drainage, and it certainly is more natural to put the steam and water in at the top and get the water out at the bottom. In the Inter-Borough station at New York, Mr. Stott's station, there are some of the heaviest of the Manhattan engines: Mr. Stott told me that he had had no trouble with them; the Manhattan engine builders fear more trouble in putting the big low-pressure cylinder horizontal than they get from the water, so they put the low-pressure cylinder vertical and keep the smaller high-pressure cylinder horizontal, and their results are equally pleasing. It is interesting to note the difference there is in efficiency between the two engines. The author gives us a test of a 3,500-k.w. set which took 16·88 lbs. of steam at 180 lbs. pressure with 80° F. superheat. Mr. Stott has published a very complete test of one of his 5,000-k.w. sets which took 17·05 lbs. of saturated steam with 150 lbs. pressure. One may generally look to larger engines as being slightly more efficient than smaller sets. Making the correction for the saturated steam and the lower pressure, I find that the 5,000-k.w. set tested by Mr. Stott took 20,300 B.Th.U., and Mr. Rider's 3,500 k.w. set with superheated steam and higher pressure took 20,900 B.Th.U. That is quite as close as we could expect two engines to test. I certainly should not expect to go into the works to test an engine on two consecutive days and obtain such close results. I think the close agreement between Mr. Stott's and Mr. Rider's tests shows the accuracy with which the tests were taken. The question of surface condensing for turbo-generator sets is very interesting. The author gives us the key to the surface of his condensers for the reciprocating sets. I find that he has allowed 6½ lbs. of steam per square foot per hour for condensing, but he has not told us what he allowed on the turbo-set. On page 270 a useful table is given showing the total cost of the plant. I am glad that Mr. Rider returns to normal ways of thinking, and has rated his plant on the normal capacity and not on the Parliamentary capacity. One rather wondered what the ratings were going to be, and the impression left, after hearing the evidence on several Bills in Parliament, was that the proper way was to reduce the estimated capital cost by every possible means while exaggerating the estimated output, thus reducing the estimated cost per kilowatt below its true value. Mr. Rider has dispensed with synchronous sets and gone in entirely for induction sets; but I note he has not yet settled how to start these induction sets, and has adopted the compromise of starting his small induction sets from the direct-current side, and starting his larger sets from the slip-ring or alternating-current side. I put in induction sets when I was designing the City plant above

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Mr. Patchell.

referred to only to the extent of one or two machines in each sub-station, so that when we had no direct current to start from we could start from the alternating-current side through the induction sets, and then get the synchronous machines away. We certainly had no trouble with those synchronous machines, although with the induction machines we had just such troubles as the author has described in the paper. If I were to set up that plant over again I certainly should put in synchronous machines in preference to induction. The experience which Mr. Rider has had with the breaking down of the coils brings up an old fact in winding that we discovered practically twenty years ago, when we began to wind high-tension coils at Milwall for the direct-current battery sets. We then found that if we wound to the end of a bobbin and back again we invariably got breakdowns. We had to wind the bobbins in sections and connect them up in series, and that is practically what the author shows in Fig. 25, system A. We had, as I have already mentioned, trouble with the induction sets through the breaking down of the early turns of the coils. We got over that by putting coils outside the machine. I am firmly convinced that there is a rise of pressure or concentration of pressure on the early turns in the coils. That may be got over by shielding through an outside device or cushioning the blow that you give to the coil by switching on the high tension. I am not at all sure that part of the defect is not initially mechanical through the sudden application of the high pressure, and that the mechanical shock leads to disintegration, which subsequently causes the burn-out and develops into an electrical fault. I am perfectly certain we had considerable rise of pressure in the early turns of those coils. I found the same thing strikingly exhibited in the station at Niagara, where some years ago I saw a transformer and a set of resistance boxes which had been made for applying up to 100,000 volts pressure on the line insulators for testing purposes. Whenever an insulator broke down they had to suspend the tests until the resistance boxes were rewound. Subsequently they put a choking coil on each side of the resistance box, and there was no further trouble. On page 291, where the author gives the cost of the sub-stations, he brings out a very interesting point. I find that the sub-station plant and buildings cost £10·24 per kilowatt. The price that he previously gives us for his generating plant runs out at £23·63 per kilowatt. He has a proportion of sub-station to generating plant of 5 to 3, or 1·7 times as much. That, I think, is a text that might be preached to some of the men who try to price out a power scheme by only advertising the generating station end of it, and yet saying they are going to supply direct current on a paying basis. It certainly gives them something to think about, because not only have we here the fact plainly before us that the cost of the generating plant is only equal to about half the total cost of the machinery and plant, but in addition to that the cables and the street work call for the provision of nearly as much again. I should like, in conclusion, to congratulate the author not only on his excellent paper, but also on

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the very clean and tidy aspect of his station. It is really a pleasure to go round a station like Greenwich. In early days, when we went round an English station and then went on the Continent and compared the state of affairs in foreign stations, we wondered why we could not do as the foreigner did. We imagined that labour was cheaper on the Continent and that that was the reason of it, but I am very glad to say that there are now stations in England which are as clean and natty as any stations I have seen, either on the Continent or in America. I think perhaps the absolutely enclosed engine had something to do with it, as it will run anywhere. It would hardly be fair to blame a man for not wiping down an enclosed engine, which would look no better when he had cleaned it; but if the engines are so designed as to make it worth while, the men will clean them. Mr. Patchell.

Mr. K. EDGCUMBE: I should like to refer again to page 260, where Mr. Rider tells us that his experience with reverse relays on the generators has led him to think that it would be better to dispense with them altogether. Three speakers in succession at the last meeting agreed with the author, but I somehow feel that the question is such an important one that it should not be passed over too hastily, and we should very much like to have some further facts from the author as to the trouble he has experienced. He tells us in the paper very little about it, being evidently a disciple of the philosopher who said, "State your conclusions, but never give your reasons; your conclusions may be right, but your reasons are almost certain to be wrong." I think that, reading between the lines, there is no doubt that his reverse relays have been guilty of cutting out healthy generators when they should not have done so. But does it follow from this that the only alternative is to do away with all protection on the generators? Mr. Edgcumbe.

It has been my experience that, in a great many cases in which this complaint has been made, the real trouble was not that reverse relays were used, but that their settings were abnormally low. I do not know what Mr. Rider's current settings at Greenwich are, but I should imagine them to be about 10 per cent. of the output of each generator. A 10 per cent. setting has become a very usual one to ask for, and some engineers even go as low as 5 per cent. This may be all right on small plants, but I cannot help thinking that with large systems, where surges have to be reckoned with, and still more where there are generators of various types running in parallel, some driven by reciprocating engines and others by turbines, there are bound to be temporary reversals of energy.

In that case there seem to be three possible courses. One is to introduce a small time lag, which is, I think, on the whole, to be deprecated, since the longer the faulty generator is left on the bars the more trouble there is likely to be. On the other hand, I think that a *definite* time lag is far preferable to an indefinite time lag depending on the alacrity of the switchboard attendant in cutting out the faulty generator (even assuming he attacks the right generator and does not pull out a sound one). Another plan (the one Mr. Rider proposes) is

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Mr. Edgcumbe.

to do away with the relays altogether, but that scarcely seems logical. The third possible method is to set the relays for a much heavier reverse current. The only objection to this is that, on the occurrence of a bad fault, the busbar volts are almost certain to fall, and with the ordinary wattmeter relay this entails a corresponding increase of tripping current. But, as a matter of fact, I do not see that even an increase of current to four or five times the normal output of the machine will injure the generator, and in any case the real solution seems to be to arrange the relays so that the tripping current is to a large extent independent of the voltage. It is not difficult to arrange the relay so that, if the voltage falls to $\frac{1}{10}$ or even $\frac{1}{20}$ of the normal, the tripping current will not be more than doubled.

This whole question is of such importance that I, for one, should very much like Mr. Rider to give us some further details of his experience, and before he irrevocably changes that little word "almost" into "quite," as he threatens to do, I should like him to increase the setting of his relays at Greenwich, and I cannot help thinking that such a course will convince him of their real utility.

Communicated: In my remarks at the meeting I confined myself to the question of relays acting when they should not; my reason being that Mr. Rider's suggestion to do away with the relays seemed to postulate this fault. It may be worth while, however, to deal shortly with the other side of the question, *i.e.*, the conditions under which a reverse relay *should* cut out a faulty generator. These are, I think, three in number:—

1. A short circuit or earth in the generator.
2. Failure of the motive power.
3. Failure of the generator field.

A fault in the generator throws a more or less non-inductive reverse load on the busbars, and is accompanied, as a rule, by a fall in busbar voltage to an extent dependent on the severity of the fault. In the case of a failure of the motive power the generator will continue to run as a synchronous motor, unless it has been pulled out of step by the "seizing" of a bearing. In the latter case the effect is similar to a short circuit in the windings, and in either contingency the result is a reverse load of comparatively high power factor. The third fault, the loss of field, has a totally different effect. It must be remembered that the engine is still under full steam, and the generator continues to feed current into the busbars. This current, which is a leading one of very low power factor, serves to magnetise the field and goes on increasing until the voltage of the faulty generator is equal to that of the busbars, which will almost certainly have fallen considerably during the process. From this it will be evident that a *reverse* relay will not trip at all with a failing field. For this reason Mr. Leonard Andrews suggested some years ago that relays should be so arranged as to trip not only with reverse currents pure and simple, but with forward leading currents of low power factor. Experience shows that such currents are never

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produced except with a failing field, and this undoubtedly gives the correct solution of the problem. Mr. Edgcumbe.

To sum up, there would appear to be no reason for the usual abnormally low settings, and, apart from a fall of voltage, a setting of 25 per cent. or even 50 per cent. of the full load would appear to be none too high. To obviate trouble due to a fall in pressure the relays should be so constructed as to be independent of this, and they should also be arranged to trip with a leading forward current due to loss of field.

There is one other point which has not, I think, been touched upon by any of the speakers, and that has reference to the protection of the inter-connectors by overload time limit relays. It would be of extreme interest to hear Mr. Rider's experiences in this matter, as such relays are far simpler than the various differential arrangements which have been suggested from time to time. Provided the time lags are accurately adjustable, and are such as to give the same discrimination *at all loads*, they should certainly afford all the protection required.

Mr. H. M. SAYERS: Mr. Rider has permitted me to mention one or two facts about the behaviour of induction motors which were discovered by measurement in one of his sub-stations, and which go to support what Mr. Patchell said just now as to the mechanical element in the failure of stator windings. A point was selected in the centre of the end winding of one of the stator coils, to which was affixed a small stylus. Then the machine was run up to speed in the usual way and switched on; and the point traced out a line showing the mechanical movement of the coil. The curve described was a figure of 8, the movement being in some cases as much as $\frac{3}{8}$ in. circumferentially and $\frac{1}{8}$ in. axially. It is clear that so much movement as that means a considerable stress upon the insulating material, and that a coil with one turn per layer as in type A given by the author will stand such a stress better than when built up with many turns per layer. It will be interesting to know if the author has taken oscillographs of the current as well as the voltage at the moment of switching in these machines, as the current is probably high, and varies with the exact phase moment of switching. The author's choice of induction motor-generators has been criticised, but I am not a bit surprised that he has not chosen rotary converters for conduit tramway work. The latter are extremely interesting machines, but altogether too lively on a duty involving heavy short circuits such as arise in conduit tramways. I am surprised, however, that he has not tried what is probably the best machine of the kind that has ever been built, the Lacour motor converter. It is a very satisfactory machine on railway work, and Mr. Roger Smith has adopted it on the Great Western Railway. I have seen his machines on various occasions, and they run extremely well. They are light and small for their output, and combine the best characteristics of the rotary converter and the induction motor-generator. The author states on page 272 that over 66 million units were delivered to sub-stations in a Mr. Sayers.

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Mr. Sayers.

year, but that does not enable one to ascertain the works cost in the stations, or to take out the efficiency of the transmission system. I am a little curious to know where the 66 million units were measured. Estimating the car-miles run during the same year as 29 millions, it works out to 2·3 units per car-mile. That is a very heavy consumption, even for the heavy London County Council cars. In the year ending March 31, 1907, according to the official accounts, the units generated were 32,782,000 for 16,267,000 car-miles, or 2·02 units per car-mile, so that for the year ending December 31, 1908, there is an apparent increase from 2·02 to 2·3 units per car-mile, 14 per cent. more than were generated at the stations in the previous year per car-mile. To that 14 per cent. have to be added the transmission losses, so that there appears to be a total increase of from 20 to 25 per cent. in the units generated per car-mile. That is difficult to understand, although I know that a larger proportion of bogie cars are now in use than formerly. It would be very interesting if the author could throw some further light on that point. I think he has dealt very clearly with the commercial position of the big station. Mr. Patchell says that we have had that from a Parliamentary point of view *ad nauseam* during the last few years. I take it that Greenwich is a pretty good example of what can be done on a below-bridge Thames-side station. The figure of 0·331d. per unit, whether that be per unit delivered to the feeders at Greenwich or to the sub-stations at the other end, is a very creditable one, but, as Mr. Snell has pointed out, it is very near what was claimed in the committee-rooms, and we are not going below that for some time to come. But it is to be noticed that that low cost is obtained on a capital expenditure of very nearly £24 per kilowatt, by no means a committee-room figure. If one works out the capital charges per unit, it makes a considerably larger addition than has been usual in the evidence laid before Parliamentary committees. Then comes in the question of the transmission losses. Mr. Rider has some sub-stations as far away as 10 miles from his generating station. Ten miles of 3-phase cable laid and joined up ready for use will cost at least £15,000 in London, and that is a considerable addition to the cost of the sub-station. Then, if the energy is delivered at 6,000 volts, with a power factor of 90 per cent., and the cable worked at 1,000 amperes per square inch, the rate of transmission is 1,404 k.w. That is below the capacity of three 500-k.w. motor-generator sets, which I believe some of the stations use sometimes. The loss at that load will be 13·7 per cent. of the energy delivered. If the most economical cable is used the total cost including capital charges ought to be about twice that; that is to say, it costs about 27·4 per cent. of the generating cost to get the energy delivered 10 miles away without conversion. So if there were another generating station only 5 miles off instead of 10, and the extra cost of coal were not increased by more than 12 per cent., there would be a net saving on the cost of the energy as delivered to the sub-stations by using two stations instead of one. I think that also is a moral which we have not learnt in the committee-rooms.

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Mr. G. L. ADDENBROOKE: Attention has already been directed to the large amount of heat lost through Mr. Rider's having to blow down his boilers 5 in. each day, and also to the question of treating the water used for the boilers, both of which points are of more importance than is usually supposed. It often happens that although water can be freed from lime it contains chlorides in solution which are not removed and which may give rise in the boiler to pitting and other troubles, and I understand that this sometimes happens in London, where water obtained from wells is not infrequently brackish. I would like to ask Mr. Rider if he could give particulars of the amount of water used for the boiler supply and what proportion of the total goes through the turbines in the form of steam, and also what is the proportion of the make-up water of the total water pumped into the boilers, and approximately the amount of water lost by blowing off. If these matters are gone into I believe that a very good case may be made out for distilling the making-up water to begin with, especially for the turbine portion of the plant. It appears to me that there would be many advantages in doing this where the circumstances are favourable, and that it would turn out to be economical also. Mr. Addenbrooke.

With turbines the condensed water is free from oil, and if distilled water were used for the making up the necessity for blowing down the boilers would be very greatly reduced. Owing to freedom from scale the boilers would be a little more efficient and would not require cleaning so frequently. Considerably smaller amounts of water would therefore be needed for the boilers, and treating, if required at all, would be greatly reduced in amount. The addition of a small amount of lime after distillation would also prevent any acidity and consequent pitting inside the boiler, and would therefore save in repairs and permit the boiler plant to be run with a smaller margin of spares.

In marine work, of course, this arrangement is very largely used under less advantageous conditions than should obtain on land, and I believe it is usually taken that the make-up water required should be about 5 per cent. of the water passing through the boilers, and it would be interesting to know what the equivalent loss is in a large installation like Mr. Rider's when working with a good load factor. With care, and if the blowing down of the boilers could be avoided, the make-up required should be even smaller, and with the cascade form of apparatus which is made to-day the evaporation of some 2½ gallons can be obtained from 1 lb. of coal, and the apparatus is simple to work. I believe, therefore, in many instances it would be advantageous to adopt this system, and with a perfectly pure water feed it is probable that there is scope for the adoption of boilers more of the Yarrow or Thornycroft type with small tubes and giving a very high rate of evaporation for meeting peak loads. The old difficulty which prevented the use of this type of boiler was that with hand firing there were obstacles to maintaining a sufficiently regular supply of steam, but with the general adoption of mechanical forms of stoker this is

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Mr. Addenbrooke.

obviated, so that the necessity for a large water reserve is greatly reduced.

I would finally like to ask Mr. Rider for further details of the large sum for buildings and foundations which is included in the cost of his generating station. No doubt local authorities are justified in spending more in this than private companies, and the buildings are of a secondary interest from an engineering point of view; but, nevertheless, interest and depreciation must be found on the capital locked up in them, and while considering an undertaking of this sort as a whole there is a certain want of proportion in only devoting a few lines to an expenditure which is nearly half the total, and which brings up the capital expenditure per kilowatt to the large amount of £23. It is the more desirable to have these figures, since building particulars are so frequently passed over by engineers, and it is in this item that estimates often come out seriously wrong.

As very large power stations are not built every day, and this is a public one, some more detailed figures would be both interesting and valuable.

Mr. Trezise.

Mr. J. M. G. TREZISE: The smallest details at Greenwich have evidently been very carefully thought out. One has only to walk through the station to see this, and I venture, therefore, to ask for a little information respecting one or two details of the high-tension switchgear. I notice that isolating plugs with insulated handles are made use of, both at the generating station and at the sub-stations. Seeing that it would hardly be safe to grip these plugs in the hand without some further insulating device, does the arrangement present any real advantage over an ordinary bare copper knife switch operated by a rod with a hook at the end? Then, again, with reference to the spark-gaps at the Greenwich station provided to protect the feeder cables, do discharges take place through them, and if so under what conditions do they act? Are any means provided for indicating if a discharge has taken place, and is any difficulty experienced in keeping them clean and in good order? Passing from the subject of high-tension switch design, there is the interesting question of straining the water for the condensers. The immense advantage of an automatic strainer to deal with circulating water from a river such as the Thames, or from canals, is undoubted; but the fact mentioned that some 15 per cent. of the water pumped for condensing leaks back through the strainer to the river without being used, and is consequently pumped to waste, appears to be a serious matter. The capacity of each strainer is stated to be 1,000,000 gallons per hour, and if we take the head against which the water is pumped as 30 ft. this means the useless pumping of 3,600,000 gallons of water per day against a head of 30 ft. It would appear, however, that with a practically constant pump pressure the waste through the strainer would remain constant whatever the quantity of water pumped; consequently if 500,000 gallons of water were being pumped the waste would amount to 30 per cent., and although the actual waste would be the same the percentage

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Mr. Trezise.

waste becomes much greater. The large amount of power required to drive the circulation water system at Greenwich has been referred to, and Mr. Bailey has attributed it to some defect in the design of the circulating pipes; but Mr. Martin Roberts, who also referred to the matter, does not agree with this view. I have endeavoured to make a calculation to arrive at the power required to pump the leakage water through the strainer. It is stated on page 265 that the two 24-in. circulating pumps each have a capacity of 12,000 gallons per minute, that is, 720,000 gallons per hour, and that the motors are each of 250 B.H.P. Now, if 720,000 gallons per hour require 250 B.H.P., the leakage water pumped to waste through each strainer—namely, 150,000 gallons per hour—would consume 52 B.H.P. That equals in a year 377,278 units. If two strainers are in use the continuous waste will amount to 104 B.H.P., which equals 754,555 Board of Trade units per year—that is, two strainers in use means a waste equal to more than three-quarters of a million units per annum, and so on with additional strainers. These figures, I think, show that a large proportion of the power required to work the circulating system is due to the loss of water through leakage in the rotary strainer, and that the item is a serious one in the cost of condensing. The disadvantage of having the pump outside, that is, on the river side of the strainer, has been referred to. Of course, the great disadvantage of this arrangement is that the strainer does not protect the pumps, and consequently it is necessary to depend on the fixed strainers in the catch-pits to protect the pumps, in which case the grids of these strainers have to be of small mesh, and perform much of the work which should fall on the self-cleaning strainer; or, as an alternative, large pumps have to be employed which will pass articles of considerable size. The consequence is that it is impossible to adopt the economical arrangement of having two or more small pumps in parallel so arranged that those in use are at all times practically fully loaded and running economically, and it is necessary to have one large pump on each line of pipes worked to to its full capacity without being varied to meet the requirements of the varying load from hour to hour. It is true that this difficulty may be partly overcome by using direct-current motors instead of alternating-current motors, so as to make it possible to vary the speed of the pumps; but the efficiency of a centrifugal pump falls so rapidly with decrease of speed that there seems to be no advantage in using direct-current motors, and it would appear that economical working can only be obtained by the use of two or more pumps in parallel, additional pumps being brought into use as required. The objection to having a very small mesh in the fixed strainer so as to protect small pumps is that the direction of flow of water in the pipes has to be reversed very frequently in order to clean the strainer, whereas if all the straining could be effected by the automatic strainer fixed outside the pumps this would not be necessary, and the direction of flow of water in the pipes would only require to be reversed at long intervals. Mr. Rider briefly refers, on page 267,

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Mr. Trezise. to the fact that pressure water is used for sealing the periphery of the strainer. It would be interesting to know how much water is used, and if it is obtained from the town supply, what it costs per annum. Some twelve months ago the author very kindly gave me the opportunity of making a rather careful examination of the condensing arrangements at Greenwich; the circulating water system from the Thames to the condensers is certainly very interesting. The advantage of carrying the pipes, immediately they leave the station, below the low-water level is obviously very great, as it prevents the possibility of air leakage—a matter of great importance in a system like that at Greenwich, where the weight of discharge water balances the head of the in-take water. But there would appear to be some disadvantage, when taking water from the Thames at any rate, in the sharp bends shown immediately inside the river wall, as in the event of a water-logged baulk of timber getting into a pipe it would be jammed at one of the bends.

Mr. Salter. Mr. J. R. SALTER: I think tramway men especially ought to be indebted to Mr. Rider for this paper, which deals so fully with tramway matters, having regard to the fact that something like 70 millions of capital are invested in tramway undertakings in this country. The first thing that strikes one who is solely engaged in tramway work about the paper is that the station might have been differently situated, so as to have obviated what must be the very heavy capital expenditure for transmission cables. If the station had been situated somewhere in the neighbourhood of Southwark a very great saving would have been made in the capital expenditure on the transmission cables. Possibly the author has considered this subject, and if he has I should like to know if he has formed an estimate of the saving in capital with a station more centrally situated, and also what such saving in capital charges would represent per annum per car-mile. The next point is the employment of storage batteries in an undertaking of this magnitude; as these batteries have only $\frac{1}{100}$ of the total capacity of the plant, I do not think it can be contended that they give any of the advantages which are ordinarily claimed for batteries, viz., the ability to shut down, an improvement in the load factor, or a saving in the copper. Having regard to that fact, it does seem strange that apparatus which involves depreciation or maintenance charges equal to 07 per cent. of the original cost in ten years, in addition to the interest and sinking fund charges, should be put down solely on the ground of convenience. The author has been very kind and candid in telling us that the conduit system is subject to many faults from which the overhead system is free, and he gives us about six pages in the paper showing the ingenuity he has displayed in getting over those faults. I want to ask him, however, to give us a few more pages dealing with the defects of the conduit system. The results at the generating station are highly creditable, but it seems to me there must be something wrong in the efficiency of the distribution or in the consuming device—that is, the motors on the cars. The only instal-

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lation of a similar size that we can make any comparison with is Glasgow. In Glasgow the consumption per car-mile is 1·25 units, and the cost 0·45d., whilst in London the consumption is 2·24 units per car-mile and the cost 0·93d. I can only assume that the costs are high because of the inherent defects of the conduit system; but if Mr. Rider got his figure of costs per car-mile down to anywhere in the neighbourhood of the Glasgow costs there would be a saving of about £40,000 a year in the generating costs, which would have represented the interest and sinking fund on a capital expenditure of £600,000. In addition to that, his current consumption would have been less per car-mile, the maximum demand less, and his generating station would consequently have been of less capacity. Again, with regard to the cost of the feeder system, there is, unfortunately, very little information given as to the low-tension feeder system. There is, however, no doubt that the cost must be enormously greater than with the overhead system, involving, as it does, the duplication of cables for the positive and negative side, owing to the impracticability of using the rail as return. I should like to ask Mr. Rider if he can give us any idea of the cost of the low-tension feeder system for comparison with the cost of low-tension cables for the overhead system. If he could give it us in terms of the cost of the number of car-miles run per route mile per annum, we could make a comparison with any overhead system in existence. Probably one of the most remarkable departures from ordinary tramway practice is the use by the author of ordinary shunt-wound instead of compound-wound generators. I can hardly believe that he has adopted shunt-wound machines to overcome the difficulties which he notes in the paper. I have never heard of any complication in working compound machines, nor have I ever had any trouble with the reversal of polarity, except with rotary converters, and he has only two of these. I can therefore only assume that the use of the shunt-wound machine has something to do with the inherent defects of the conduit system. May I suggest that probably his low efficiency, both in transmission and distribution, may be partly accounted for by the use of shunt-wound machines. The applied E.M.F. at the motors must vary more than with compound-wound machines, and when the load is heavy the E.M.F. must be very low. The speed of a tramcar must be maintained at the expense of current, and consequently the consumption per car-mile goes up and the efficiency of the motors and the whole system goes down. Mr. Salter.

Mr. H. Brazil: I wish to make a few remarks with regard to earthing resistances in the neutral point, and should like to congratulate Mr. Rider and Mr. Shaw on the ingenuity they have displayed in getting out the device illustrated and described in the paper. When, however, one looks into the amount of wiring required, the number of switches involved, and the cost of the whole apparatus, one is the more inclined to believe that Mr. Rider's remark that his station is the only one fitted with this device at present, is likely to remain true in the future. Mr. Brazil.

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Mr. Brazil. With regard to the working of the apparatus, during the interval which elapses between the time when the one machine whose neutral is earthed is shut down and another one is being found by this device to which the neutral point can be attached, the system remains with its neutral insulated; further, when it becomes necessary, as sometimes happens, to divide the system into two or more parts, only one of these parts can be earthed by this device. This, I think, is a dangerous state of affairs, in that if a system which normally has its neutral earthed is left with the neutral insulated for any length of time, large rises of potential above earth, which the system is not accustomed to, may occur, and these rises will put a severe strain on the insulation of machines, transformers, cables, etc.

I think Mr. Rider will agree that if we have an earth resistance only without any such apparatus as he describes, the desirable points are: *first*, the ohmic value shall be sufficiently high to render the shock to the system at the time an earth occurs as small as possible, and yet be low enough to enable the automatic cutouts on the faulty feeder to trip shortly after the fault occurs; *secondly*, it should be capable of absorbing a very large amount of power for a reasonable time without injury, and when left unused should not deteriorate owing to dampness or other causes; *thirdly*, it should be so arranged as to interpose between the neutral points of the several machines as high a resistance as possible, having due regard to what is required of it when an earth comes on.

I venture to suggest an arrangement of special carbon powder resistances which will satisfy the above requirements, and possesses several advantages over that described by the author, especially as regards cost. The resistance itself consists of a fireclay trough in which is placed a special carbon powder made by the Morgan Crucible Company. The depth of the powder is about ¾ in., and, being open to the air, it is free to expand. These resistances are provided with carbon terminals of ample surface, so that the contact with the powder is good, and they can be connected in series or parallel in any arrangement that may be desired.

The special feature about this resistance is that whereas with the ordinary iron grid type the ohmic value is lowest at the time the fault occurs, and increases as it heats up, with the carbon powder type the resistance is at its highest value when cold, and may be designed to decrease to any extent one pleases down to, say, $\frac{1}{15}$ of its original value. This variation, which in most resistances would be considered a disadvantage, is a valuable feature, as I will explain presently, when the resistance is used for earthing the neutral point. Within certain limits, for every voltage per inch run of the troughs, there is a definite value to which the resistance attains, and at which it remains very nearly constant for some considerable time, extending in some cases to one hour. The carbon powder, under these circumstances, is of course at a good red heat, but as it is enclosed in fireclay no trouble arises, and after this prolonged heating it remains unaltered.

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Mr. Brazil.

These resistances are capable of absorbing very large amounts of power without injury, and even when they are overrun it is a very simple and inexpensive matter to put in fresh powder and thus restore the resistance to its original condition.

As an example of the amount of power absorbed, I would mention that a fireclay trough whose internal dimensions are approximately 20 in. × 6 in. × 1 in., will deal with 12 to 15 k.w. for about 10 minutes, and 8 to 10 k.w. for half an hour or more. If the resistance is only required to be on for 2 or 3 minutes, a considerably greater amount of power can be absorbed.

For the purpose under discussion, the resistance made up of a number of units arranged in series and parallel, is connected as shown in Fig. D. This represents three machines with their neutral

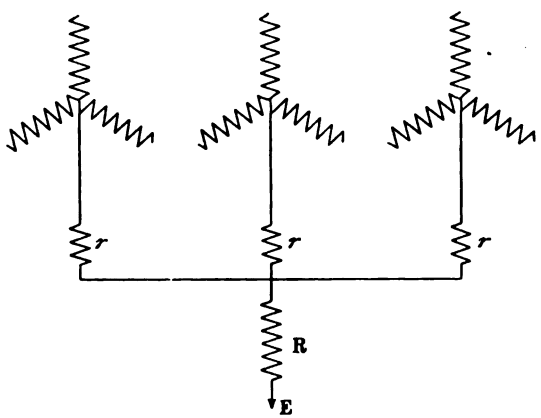

FIG. D.

points connected, first of all through small resistances *r*, *r*, *r* to a common busbar, and then through a larger capacity resistance R, having a higher value to earth. Under normal conditions, the small resistances *r*, *r*, *r* being cold are at their highest value, and as there are two of them in series between any two neutral points, the current between these two points is reduced to a small figure. Incidentally I should like to suggest that as the current passing between the neutral points of the machines has a frequency three times that of the normal, small choking coils should be put in place of these resistances *r*, *r*, *r*. Between the neutral points of any two machines we should then have two choking coils in series, and the frequency being three times the normal, the choking effect would be six times as much as that between any one machine neutral and the common busbar. This arrangement would reduce the current between the neutral points, but would not oppose to any great extent the current of normal frequency going to earth.

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Mr. Brazil. Returning now to the earthing resistance itself, if we take the author's figure of 3·5 ohms as being the highest admissible in order that when an earth occurs on the end of a long feeder the automatic cutout on that feeder shall act, and assuming that the carbon powder resistance reduces to this figure of 3·5 after having decreased to $\frac{1}{5}$ of its original value, it is clear that the resistance when cold may be as much as $3{\cdot}5 \times 5 = 17{\cdot}5$ ohms. In the system under discussion, the voltage to earth from any pole is 3,700, so that when a fault occurs the current that passes, if the fault has no resistance, will be $3{,}700 \div 17{\cdot}5 = 212$ amperes with the arrangement I suggest, as against $3{,}700 \div 3{\cdot}5 = 1{,}050$ with the resistance described in the paper. This current of 212 amperes should be sufficient to trip the automatic cutout on the faulty feeder; but if it is not, the resistance will heat up and automatically decrease until just sufficient current passes to enable the automatic to open circuit. As by far the largest number of faults are from one phase to earth and not between phases, I venture to suggest that this is a very important advantage, in that not only is the shock to the system when an earth occurs reduced very considerably, but when the faulty feeder is cut out, the current broken is only that sufficient to trip this automatic switch, and not, as in the other case, the maximum current that the resistance will allow to pass.

[t] Summarising the whole matter, I should like to point out that under certain circumstances the author's arrangement leaves the system with its neutral insulated, and when it has to be divided into two or more parts, only one of these parts can have its neutral earthed; the arrangement I have suggested is not open to these objections. Further, when a fault occurs, the current with Mr. Rider's arrangement is over 1,000 amperes, whereas with mine it is only 212. Finally, the cost of the carbon powder resistances would be only about $\frac{1}{10}$ of that of the special arrangement described by the author.

The drawings given in the paper show a very large number of multi-gap type of arrester, and it would be very interesting if Mr Rider would give some particulars as to the voltage at which they spark, approximately what current passes, whether they act often, and if he has had any trouble with the carbon rod resistances.

It is very difficult to obtain any information as to the working of these arresters, but, as Mr. Rider has so many installed, he doubtless will be able to give some valuable information on the above points.

Mr. Clark. Mr. A. B. Clark: I would like to ask the author one or two questions with reference to the condensing system. I see from the diagram on page 266 that there are two water meters in the circulating water system, and I would like to ask the author if he can tell us how much water they pass in a given time, and also what vacuum the two air-pumps maintain at the air-pump barometric tubes, and their dimensions and revolutions, so that we could get the figure as to the amount of air in the circulating water per 1,000 cub. ft. of water. That is the trouble we had at Chelsea at the beginning of our work. Going further back in the paper, I would like to ask for some more informa-

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tion about the earthing resistance. Recently we have had to design a new one, and I should like to ask Mr. Rider what is the weight of his, as I find that to carry 6,000 k.w. for 10 minutes without breaking it up some 5 or 6 tons of metal are required. If there is an open circuit on the earth resistance produced during operation, we find we have more trouble. With regard to Fig. 14, the diagram of the switchgear, there are apparently two low-tension auxiliary feeders coming off the same busbar. If anything goes wrong with that section of busbar then his auxiliary motors will naturally stop. In that case he will get no circulating water, and his machines will go to atmosphere. No doubt a considerable load can be got out of reciprocating engines on atmosphere, but with turbines more work is done below atmosphere than above atmosphere, and I am afraid he will have considerable trouble in carrying any load if the auxiliary motors fail through both feeders being taken off the same section. On page 256 a test on the reciprocating machines is given, and some very good results are mentioned. The efficiency of the generator is apparently better on half load than full load. The consumption of water per kilowatt-hour is 16·67 lbs. at half load, while at full load it is 16·88 lbs. As the water per I.H.P. is higher at half load than full load, the efficiency of the generator must be more, and that should be marked in red ink, because it is rather unusual. A little further back in the paper some boiler tests are given. These are certainly small boilers as previous speakers have pointed out, but the author manages to get quite a large evaporation from them, and apparently at the very good efficiency of nearly 80 per cent. But if you start to work back from the actual flue temperature, you find that the amount of air supplied per lb. of coal is only about 12 lbs., in which case the CO_2 is something like 19 per cent. That is rather unusual, and in fact practically impossible, and therefore I would like to ask if there is anything wrong with this test. I think a temperature of 620° F. at the back of the boiler at that load is about a correct temperature. Then I should like to ask how he measured the water—whether it was measured by a water meter or in calibrated tanks. It would look as if a water meter was used owing to the fact that the temperature of the feed water is high. I rather doubt the water meter myself, it might easily be 2 or 3 per cent. wrong. I notice that the factor of evaporation is given as 1·66, but speaking from memory I fancy the figures should be 1·06. Probably the efficiency should be about 74 per cent., which would be quite a good result, because although 80 per cent. is quite usual at low evaporation, it could scarcely be obtained with the rate at which the boiler is worked. The author gives on page 241 the contract under which the coal is purchased. On looking through a large number of analyses and tests of coal I find it is a very poor coal indeed that does not reach 13,000 B.Th.U. when dry; and I think that the value given in the paper of 12,500 B.Th.U. might easily be raised to 13,000. Then, again, the moisture is given as 10 per cent. I find that where washed coal is used less

Mr. Clark.

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Mr. Clark. moisture is obtained than with unwashed coal, owing to the fact that it is really the dirt in the coal that retains the moisture. I find that that figure might easily be 7, and even then it would be quite fair to the coal contractors. Altogether that schedule for purchasing coal seems to me to give too much allowance to the coal contractor, and I should judge that the engineer benefits very little from it. With regard to the proportion of small coal—namely, 20 per cent.—from my experience I should say it could easily be 15 per cent., and that the coal should be rejected if it was above 20 per cent.

Mr. Howe. Mr. G. W. O. Howe: It has already been pointed out in the discussion that the trouble due to the breaking down of the end coils of the stator windings of the induction motors is by no means new. Makers have for many years put extra insulation on the end coils of transformers and motors. I doubt whether the device adopted by

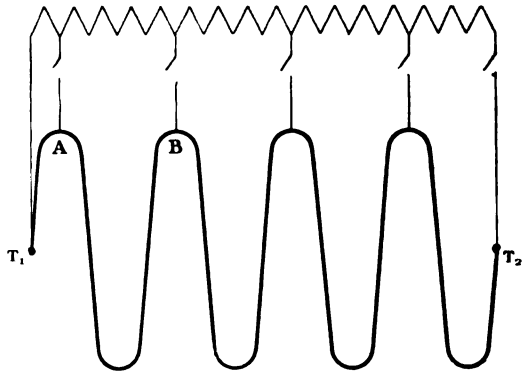

Fig. E.

Mr. Rider of putting choking coils in series with the machine is the best way out of the difficulty. I would suggest another method by which all shock to the motor winding would be prevented. By shock, however, I mean electrical shock and not mechanical shock. The mechanical shock and the initial rush of current are quite unconnected, I think, with the breaking down of the end coils, although both depend on the value of the supply potential difference at the instant of closing the switch. Mr. Partridge suggested that the rush of current depended on the magnetic condition in which the iron was left, but although this is an important point when dealing with transformers, I doubt very much whether an induction motor will retain much magnetism, as both the air-gap and the rotation on slowing down tend to wipe it out. In order to get a clear idea of the cause of the breaking down of the end coils, I have had some diagrams made. Fig. E represents diagrammatically the winding of the stator. If the switch is closed at the moment of maximum potential difference the terminal T_1 may suddenly be raised to a potential of 10,000 volts above the terminal T_2.

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When the motor is worked normally, this state of affairs occurs, say, 50 times per second, but it has then been gradually reached by increasing the potential difference from zero, whereas in the present case it has been instantly attained. Fig. F represents a pipe filled with a heavy liquid like mercury, or filled with water, but containing a number of heavy sliding plugs or pistons distributed throughout its length as shown. This is very analogous to the electric case, and will appeal to those who may be more familiar with inertia and momentum than with self-induction and capacity. An alternating current or flow can be produced by working the plungers up and down. As in the actual winding we have here a small resistance due to pipe friction, but a large resistance to sudden change due to the inertia of the heavy liquid or plugs. This latter is exactly analogous to the self-induction of the windings, which offers no opposition to a steady current, but opposes

Mr. Howe.

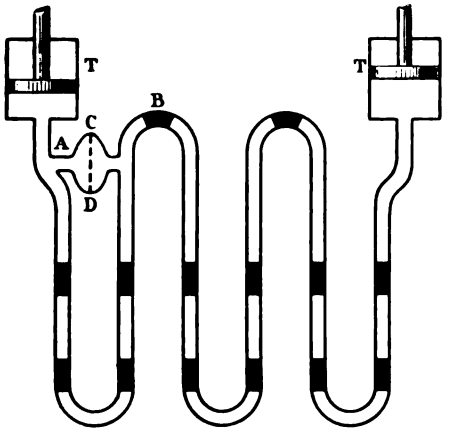

FIG. F.

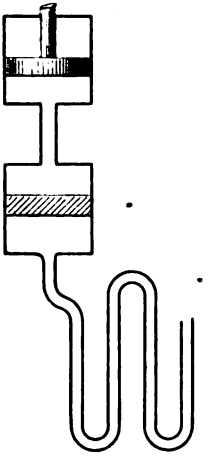

FIG. G.

any sudden change of current. If, instead of working the pistons steadily up and down, we apply a sudden blow to the left-hand one, it is obvious that the force of the blow will be taken almost entirely by the liquid or heavy plugs in the first part of the tube, their inertia entirely shielding the liquid at B. Hence we shall have the full terminal pressure across the first bend of the tube, or, in the electrical case, the first coil of the winding. Now the points A and B are close together, but separated by the dielectric, perhaps a few layers of impregnated cotton, or, if the impregnation is not complete, a thin layer of air. Hence, we have here a condenser which I have represented in the hydraulic analogy by a rubber diaphragm C D. If A and B are at different potentials the diaphragm will be strained, and if the potential difference exceeds a certain value, will be ruptured, that is, the insulation will break down. It might be objected that as the

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Mr. Howe. liquid in the hydraulic analogy is incompressible, there would be no tendency to distend the diaphragm. We must remember, however, that each coil of the stator winding has a certain relatively large capacity to the iron in which the coil is imbedded, *i.e.*, to earth. In the hydraulic case this is represented by making the tube of rubber, but we will not press the analogy any further. Mr. Rider's device of putting a choking coil in series with the winding is analogous to putting another vessel in series with the tube and fitting it with a heavy sliding piston. The inertia of this piston protects the tube from the sudden blow. The first method which suggested itself to me was to place a non-inductive resistance in parallel with the motor before closing the switch, tappings being taken from the resistance to the connections between the stator coils. This shunt could be made of high resistance and need only be in use for a fraction of a second. It could be automatically disconnected by pushing the main switch home. I need hardly point out that this would be analogous to a small bore pipe connecting A and B and all similar points. A previous speaker (Mr. Jenkin) mentioned that the abnormal pressure rise could be detected by a spark-gap but could not be seen on an oscillograph. It is probable that, even if the oscillograph could record such a rapid rise of pressure, it would act as a shunt and thus prevent the rise. Another method, and one which is probably far preferable, is to put a number of condensers in series across the terminals, and to tap off from the wires joining the condensers to the wires joining successive stator coils. These condensers can be fitted once for all and left permanently connected.

Mr. Collis. Mr. W. H. COLLIS (*communicated*): In the Lister Drive Station of the Liverpool Corporation there are seven 2,000-k.w. turbo alternators, 4 of one type, and 3 of another, which generate electricity at 6,000 volts 3-phase. The stators are star connected. The neutral points are connected without resistance to earth—*i.e.*, to the water system of the city. The output of the alternators is carried to the switchboard by means of 3-phase lead-covered and armoured cables. The armour of these cables is earthed at Lister Drive also on to the water system.

Under these conditions when several alternators were running, it was found that there was a considerable circulation of low-voltage alternating current in the armour of the cables; in fact, on one occasion the armour was found arcing where it was supported in a metal hanger owing to the current passing from the armour to the hanger, and through the hanger to the armour of other cables.

This has been prevented by insulating all the cables from metal hangers. Experiments were made, and it was found that practically no interchange of current took place between similar machines, but the interchange only took place when dissimilar machines were running. It was, therefore, decided to group the alternators into two sets, one set of 4, and one set of 3, and to arrange the earth connection so that either group could be earthed. In future one group only will be earthed at a time, and it is expected that this will do away with the

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trouble that has been experienced with these currents in the earth leads of the neutral points. Mr. Collis.

Mr. F. FORREST (*communicated*): One of the most interesting features of the London County Council tramways system is that 75 per cent. of the sub-station plant consists of induction motor-generators, and this would indicate that the author is absolutely satisfied with the general superiority of this type of plant over rotary converters for tramway work. This is quite contrary to the general consensus of opinion both in this country and in America among engineers who have operated both types of machines, and my own experience is that for the rough and tumble of traction work there is nothing quite so good as the rotary converter, especially if the frequency is as low as 25 cycles. As an example of their reliability, I may mention that in Birmingham, where rotaries are used entirely both for lighting and traction, there has not been a single machine or transformer failure during the 2¼ years they have been running. The number of rotaries installed is 21, in various sizes between 300 k.w. and 1,500 k.w., and totalling 9,100 k.w. The trouble with the end coils of the motor stators has been experienced by nearly every engineer who has used high-tension induction motors, and the method of switching in through a choking coil is the best and safest way of overcoming the difficulty. The author is apparently satisfied with a sub-station efficiency of 75 per cent., whereas if he had adopted rotaries this would have been at least 82 per cent. Mr Forrest.

The plant load factor of a tramway sub-station will approximate to 45 per cent.; therefore, in comparing the operating efficiency of the two types of plant, their efficiencies at half load is of more importance than at full load. The following efficiencies are not far wrong for machines of 500-k.w. capacity, 550 volts, 25 periods:—

Load.	Rotary.	Induction Motor-generator.
	Per Cent.	Per Cent.
½	88·5	81·0
¾	91·0	85·5
Full	91·5	89·0
1¼	92·0	89·2

I should also like some information with regard to the enormous array of spark-gaps which have been installed at Greenwich. Have any of these ever been known to operate before the star-point was earthed at the generating station? If not, would it not be better to scrap them entirely, and so get rid of a possible source of trouble?

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Mr. Chattock.

Mr. R. A. CHATTOCK (*communicated*): On page 260 Mr. Rider states that his "experience with reverse-current relays has almost converted him to the opinion that the generators should have no tripping relays of any kind whatever." It would be interesting if he would give us some further explanation of the reasons that have induced him to adopt this opinion, as I take it that he must have experienced considerable trouble with this class of apparatus in order to induce him to make such a sweeping statement against it. I would say that I also have experienced great difficulty in obtaining similar apparatus that would operate satisfactorily, but I believe that I have now obtained, in connection with the high-tension 3-phase switchgear that has been installed by the British Thomson-Houston Company at the Birmingham Corporation generating station, a reverse-current relay which can be relied upon to act under the condition of a failing field, and also of a reverse or motoring current, and which will also be unaffected by any condition of forward current as long as the field current is normal.

Mr. Rider's experience in connection with earthing the central points of the star windings of the stators of the generators is also very interesting, and the arrangements he has adopted to get over the disadvantages of a solid earth connection are very ingenious. I am of the opinion, however, that with a pressure as low as 6,600 volts earthing of the central point is not a necessity. The extra expense involved in providing slightly heavier insulation on the feeder cables of a non-earthed system is not heavy, and I consider that in view of the increased reliability of the distributing system it is fully justified. I know of at least three cases in which workmen have come in contact with the outers of an unearthed 3-phase E.H.T. system, and they have recovered from the shock. If this system had been earthed there is no doubt that the men would have been killed. On an earthed system greater expense is entailed in connection with the protective devices as these have to be operated from three phases instead of from two only.

I am aware that on systems where a much higher pressure is used, it is practically imperative to earth the central point, as in case of an outer going to earth the strain on the system would necessitate the provision of very much heavier insulation throughout, and the cost of this would probably be prohibitive. Mr. Rider does not indicate how the arrangement he has finally adopted has answered, and it would be very interesting if he would give us his experience of the operation of his system under conditions of breakdown.

Mr Brown.

Mr. J. FIDDES BROWN (*communicated*): I shall be glad if the author would give information as to the weight and seating capacity of the cars, the average speed per hour, and the consumption of energy per ton-mile, stating, as regards the last item, what it includes.

Dr Sumpner.

Dr. W. E. SUMPNER (*communicated*): The automatic earthing switch described by Mr. Rider is a complicated piece of apparatus. No one will consider its expense if it really safeguards an important generating station, such as that at Greenwich, from a source of danger, while the fact that the switch has been actually designed and used will

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be accepted as convincing evidence that such a danger exists. But it appears questionable whether this apparatus is the best one to use for the purpose in view. Dr. Sumpner.

The effect of third harmonics in the phase voltages of star-connected alternators, with the star-points all earthed, has been frequently pointed out. Mr. Brew, of the Dublin Lighting Station, first drew my attention to the matter several years ago, and showed me some oscillograms he had taken of the triple-frequency earth currents occurring under such conditions. But so far as I know no data of the voltages corresponding with these harmonics have been published in reference to any station, and I doubt whether such voltages have been

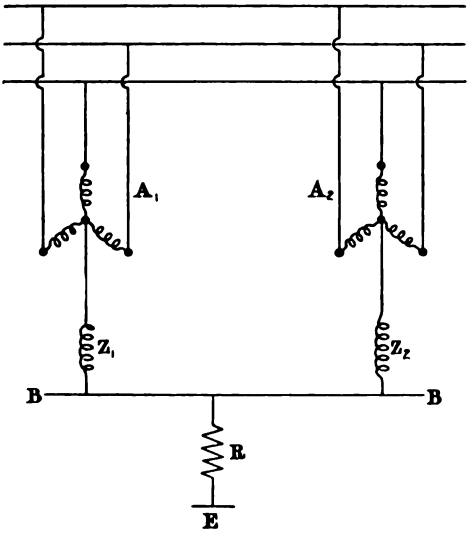

FIG. H.

actually measured. Oscillograms are pretty things, but are useless for exact data: and until definite measurements are obtainable I do not know that any one can estimate the true importance of these harmonics, unless it be from actual experience of their effects.

I wish to make the suggestion that each alternator should have its star-point connected to an earthing bar through a choking coil, and that the earthing bar should be well earthed through a low resistance of the usual kind. The sketch shows two star-wound 3-phase alternators A_1, A_2 earthed in this way, and parallel connected to the mains. Z_1 Z_2 represent the choking coils, and R the earthing resistance.

Under these conditions, if the distributing system is insulated from earth, as will normally be the case, the resistance R will have no current through it, and the earthing bar B B will be at zero potential. The point is that each of the impedances Z_1 Z_2 will take a voltage repre-

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Dr. Sumpner.

senting the third harmonic voltage in the windings of the corresponding alternator, and will normally choke down any current these voltages tend to cause. Moreover, these choking coils will form essentially the only impedance in the path of the current caused by the third harmonic voltage. The three windings of each alternator are so joined up in parallel that they constitute a non-inductive resistance so far as the current of triple frequency is concerned, and hence when two alternators are parallel connected with star-points earthed in the ordinary way it is possible for a third harmonic voltage of small magnitude to cause quite a large current circulating around the machines. It is probably owing to this fact that appreciable currents have been observed due to the third harmonic voltage, for if the windings of the alternator acted as a choking coil, the high impedance of this for currents of triple frequency would reduce any such currents to negligible magnitude.

In the absence of actual data I can only guess the magnitude of the voltage corresponding with the third harmonic. Let us assume there are three alternators in parallel—the first an ideal alternator with no harmonic in its voltage; the second an ordinary machine with a third harmonic voltage of, say, 2 per cent. of the phase voltage; and finally an abnormal machine with a third harmonic voltage of 10 per cent. of the phase voltage. Assuming the voltage from the star-point to line is 5,000 volts, the three third harmonic voltages will then be 0, 100, and 500 volts. The ideal machine will have its star-point at exactly earth potential, and can be joined direct to the earthing bar without using any choking coil. The choking coil for the ordinary machine will be subjected to 100 volts, while that for the abnormal machine will have 500 volts upon it. These voltages would cause very large currents through the machine windings were it not for the choking coils. With their aid the currents can easily be reduced to negligible values, while the voltages on these choking coils will indicate important facts about the alternators.

Now, without discussing details of the automatic earthing switch described in Mr. Rider's paper, let us consider the results it secures. These appear to be three in number. In the first place, any alternator which is shut down has its star-point disconnected from earth. No advantage is claimed for this result, and earth potential would appear to be the safest of all potentials for an unused machine. Again, only one acting machine is earth connected at any given moment. The object of this appears to be two-fold. Heavy earth currents between two machines due to the third harmonic voltage are prevented. The choking coils now suggested seem to secure the same result in a simpler fashion. Another result of the switch is that, if an earth occurs on one of the phases, only the alternator actually connected with earth is called upon to supply the short-circuit current, so that the "voltage of the whole station" can be maintained "pending the opening of the time limit circuit breaker." But the choking coils here suggested could easily be designed to prevent serious earth currents even in this case.

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Dr. Sumpner.

The object of the earth connection is to keep the neutral points of the alternators at earth potential, not to encourage leakage currents to earth. If it is desirable for one of the alternators to be available to force current through a fault, all that is needed is to connect the neutral point of its windings direct to the earthing bar, omitting the choking coil. The arrangement of choking coils above suggested forms a simpler and more certain safeguard than the automatic switch. The cost may possibly be as great, but in this matter safety is the first consideration. The choking coils can be made to give valuable information about the machines. They are approximately at earth potential, and the voltages or currents they take might possibly be utilised to work safety appliances.

Some one may object that, according to the above figures, the star-points of the generators, instead of being kept at earth potential, differ from it by 100 or 500 volts. But the choking coils are not the cause of this, and nothing can possibly alter it, except those heavy earth currents which the automatic switch is designed to prevent, or such changes in the structure of the alternators as will do away with the third harmonic voltages. These voltages exist on the various parts of Mr. Rider's automatic switch, and are only reduced to zero on that switch which is connected to earth by producing a corresponding shift in the values of the line voltages to earth.

Mr. Hollis.

ERNEST P. HOLLIS (*communicated*): The currents which flowed between the generators by way of their neutral wires when the star-points were earthed were undoubtedly due to the third harmonics. In a paper I read before the Newcastle Local Section of the Institution, in January, 1907, I gave this point considerable attention. Many engineers prefer to have the earth circuit to the star-point of as low an impedance as possible to facilitate the clearing of cable faults when they occur, and for other reasons. At the time I suggested two schemes for limiting these harmonics: first, inserting an inductance in the earth circuit of each generator, which, while having an impedance of $p L$ to ordinary currents, had an impedance of $3 p L$ to the third harmonics; secondly, "resonating" the earth circuit. If a capacity K and an inductance L be introduced into the earth circuit, for currents of normal frequency, the impedance is given by $p L - \frac{1}{p K}$, and for the third harmonics by $3 p L - \frac{1}{3 p K}$. If, now, we arrange the capacity and inductance so that $p L = \frac{1}{p K}$, then the impedance to short circuit and other currents of normal frequency is 0, and to the third harmonics it is $3 p L - \frac{1}{3} p L = \frac{8}{3} p L$. This impedance can be raised to any desirable value without having the slightest effect on short-circuit currents, while the third harmonic currents, which are caused by only a slight difference of pressure, will be almost entirely eliminated.

Mr. Andrews

Mr. LEONARD ANDREWS (*communicated*): Mr. Rider has given us a very full statement of the result of an important experiment, viz., that

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Mr. Andrews.

of abandoning the original scheme providing for two generating stations in the centre of the area of supply in favour of one larger station entirely outside that area, having the advantage of a waterside site. Two or three speakers eminently qualified to express an opinion upon the matter have entirely supported Mr. Rider's action, but many others who have closely studied the subject think that better results would have been attained with the original scheme. The settlement of such an important matter should not depend upon mere expressions of opinion but upon actual facts. The only solid fact contributed to the discussion, and having any bearing upon the matter, was Mr. Roger Smith's statement that he is paying a lower price for coal of greater heating value delivered at his works at Park Royal. Mr. Rider's reply upon this point will be awaited with the greatest interest by many of us.

Mr. Hammond made a somewhat sweeping general statement that stations situated on riverside sites were the cheapest method of generating electricity. Such a statement would have been of the greatest value if substantiated by actual particulars of capital and running costs that might be compared with other stations not having the advantages referred to, but working under otherwise similar conditions. Mr. Hammond added that Mr. Roger Smith contented himself by describing how cheaply coal could be obtained, but he did not enter into the condensing part of the question at all. It is obvious that an important question of this nature can only be properly considered in its entirety; but for the purpose of discussion it may be useful to compare the information Mr. Rider has given with some particulars available from various other sources.

In the discussion of a recent paper read before this Institution the authors were taken to task for assuming a total capital expenditure of £14 per kilowatt installed complete with cooling towers, and were told that if a riverside site had been selected instead of cooling towers the capital outlay would have been considerably less. In view of this it is somewhat surprising that Mr. Rider's actual capital outlay of £23·63 per kilowatt installed for riverside plant has been allowed to pass without comment.

Considering some of the items in detail, cooling towers for dealing with an output equal to that of the Greenwich station could have been erected complete for less than £30,000. Taking interest and sinking fund at 7½ per cent., and adding 2½ per cent. for maintenance and repairs, the fixed charges on the cooling towers would amount to £3,000 per annum. Mr. Rider's expenditure on pier and river work has been over £60,000. The repairs on this would probably be much lower than on the cooling towers, and might be covered by ½ per cent. per annum, making a total annual charge of 8 per cent., or £4,800. The above item does not cover the very heavy capital outlay that must have been incurred in the elaborate strainers that have been found necessary for dealing with Thames water. On the other hand, it may be argued that some of the expenditure under this heading should be

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Mr. Andrews.

charged to coal-handling plant. I understand, however, that one of the advantages of the original Camberwell site was that an elevated siding would have been constructed in connection with the existing railway from which the coal could have been shot directly into the bunkers from the railway trucks. It is probable, therefore, that the total cost of coal and ash-handling plant, under the original scheme, would not have amounted to more than Mr. Rider's cost of £18,500, plus the cost of the water strainers. It is often argued against cooling towers that they occupy so much extra ground space. The ground space required for cooling towers of the capacity under consideration would be about 5,000 square yards. Assuming a ground rent of 1s. per yard per annum, an additional expenditure of £250 per annum would be incurred under this heading. One of the disadvantages of cooling towers is the amount of energy expended in pumping water to the top of the towers. It is estimated that the power required for dealing with the output Mr. Rider gives of 91 million units per annum would be 2½ million units per annum, and taking the cost of this current at 0·34d. per unit, the annual charge under this heading would be £3,240. Another serious item is the cost of the extra make-up water evaporated from the cooling towers. In the case of the Camberwell site it was proposed to sink a well from which the water required could have been obtained at an estimated cost of less than 2d. per 1,000 gallons. It is estimated that the water evaporated from cooling towers would amount to 280,000,000 gallons per annum, the cost of which, at 2d. per 1,000 gallons, would be £2,340.

Many engineers who have erected plants on riverside sites have had to contend with heavy additional outlay, owing to the difficulty of getting good foundations. At one riverside station which I visited a few weeks ago, the total cost of buildings had been £5·44 per kilowatt installed. Of this amount only £2·14 per kilowatt had been expended on the actual super-structure, the remaining £3·3 per kilowatt had been spent on costly foundations owing to the close proximity of the site to the river bed. It would be interesting to learn whether Mr. Rider's apparently very high capital outlay of £9·82 on land and buildings is attributable to the same difficulty.

It is sometimes argued that a lower fuel consumption will be obtained at a riverside station owing to the lower temperature of the cooling water. This does not appear, however, to be borne out in practice. Mr. Rider's fuel consumption of 3·1 lbs. of coal per kilowatt-hour, the calorific value of the coal being 12,500 B.Th.U. per lb., corresponds to a thermal efficiency of 9·05 per cent. The fuel consumption at the Pinkston station of the Glasgow tramways undertaking is 3·05 lbs. per kilowatt-hour, the calorific value of the coal being 12,000 B.Th.U. per lb. The overall efficiency of the Glasgow plant is, therefore, 9·3 per cent., or 0·25 higher than Mr. Rider's. The load factor of the Glasgow undertaking is only 37·5 per cent., against Mr. Rider's 47·75 per cent. Mr. Rider has the supposed advantage of a plentiful supply of water at a low temperature, whereas

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Mr. Andrews.

the Glasgow undertaking obtain their water from a canal, the flow of water in which is very small, and the intake and outlet of the circulating water pipes are within a few feet of each other. The result is—the temperature of the cooling water is often quite as high as it would be at the base of cooling towers if these were used. It appears, therefore, that any advantage in this respect must also be abandoned.

The above items show on the whole some advantage in favour of water-side sites as compared with cooling towers. We have, however, to consider on the other side the extra capital outlay on feeders with the extra transmission losses and the cost of converting that portion of the total current, which would have been generated as direct current if the stations had been placed in central positions.

It is practically impossible for an outside person to make any estimate of the high-tension feeder losses and extra capital charges without fuller particulars of the distribution of the load throughout the area. The extra cost of converting a portion of the current to direct current can, however, be approximately estimated.

It is understood that under the original scheme it was proposed to instal 6,000 k.w. as direct current, or 20 per cent. of the total plant installed. It may be assumed, therefore, that at least 20 per cent. of the total output would have been generated and distributed as direct current. Now, Mr. Snell in his paper on "Cost of Electrical Power for Industrial Purposes," * gave the difference in cost between E.H.T. current and direct current on a 50 per cent. load factor as 0·466d.–0·344d., from which it may be taken that the cost of conversion, including capital charges, is 0·122d. for this load-factor.

The cost of converting 20 per cent. of 91,000,000 units will therefore be 18,200,000 units at 0·122d. = £9,250.

It appears from the above that the advantages and disadvantages of a water-side site may be represented by the following balance-sheet :—

Dr.	£		Cr. £
Pier and river work, £60,000 at 8 per cent.	4,800	Reduced transport	—
Converting E.H.T. to direct current, 18,200,000 units at 0·122d.	9,250	Cooling towers, £30,000 at 10 per cent.	3,000
		Extra ground rent, 5,000 yards at 1s.	250
		Pumping water, 2¼ million units at 0·34d.	3,240
		Extra make-up water, 280,000,000 gallons at 2d. per 1,000	2,340
		Reduced coal consumption...	—
		Debit balance in addition to extra costs of transmission	5,220
	£14,050		£14,050

* *Journal of the Institution of Electrical Engineers*, vol. 40, p. 316, 1908.

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It appears from the foregoing that at the time Mr. Rider started the Greenwich scheme there was little to choose, as far as generating charges are concerned, between the respective systems. Now, however, since the economy and reliability of large gas engines have been proved, the entire aspect of the problem has become changed. Mr. Andrews.

At the present time it would be possible to put down gas-driven generating stations (one south and one north of the Thames) at a lower capital outlay than has been expended on Mr. Rider's scheme, and to guarantee that the total annual running costs should not exceed £60,000 for the output covered by Mr. Rider's running costs of £92,208.

Mr. J. T. IRWIN (*communicated*): With reference to the breakdown of the end coils of the induction motors, Mr. Rider is not the only one who has had trouble of this kind, and as voltages get higher and overhead wires subject to larger inductive effect from lighting discharges become more general, the trouble is likely to increase instead of decrease. Mr. Irwin.

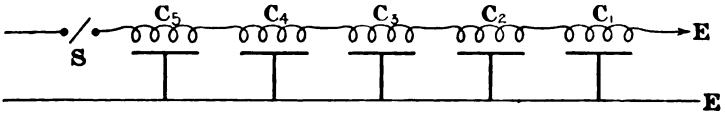

FIG I.

In Fig. I, C_1, C_2, ... C_5 are the coils of an induction motor, each of which has a capacity to earth. The problem that has to be solved is how to arrange that even for very rapid changes of pressure, such as those produced by switching on to the mains or short-circuiting the machine, the potential difference across each of the coils shall be approximately the same, and not be piled across one of the series. In considering the very rapid changes which operate in a case like this, we have to remember that a coil with a comparatively high inductance behaves almost like an insulator, and the capacity between turns is probably much more effective in allowing a current to flow through to the different coils than the copper portion of the circuit acting as a conductor. On the other hand, a condenser, for a very rapid change of voltage, acts as a short circuit. This gives us immediately the reason why all the voltage is piled across the first few turns of the first coil, as the capacity current of these turns to earth is so much greater than the capacity current flowing through the coil to raise the potential of the next coil. If the potential at a short distance along the first coil is nearly earth potential, and the potential at the end of the coil 5,000 or 6,000 volts above earth, we have this difference of potential tending to cause breakdown in the insulation between the first few turns.

To prevent a breakdown, the insulation on the end coil has to be increased, or else the rate of charge of potential has to be diminished, by putting a choking coil in series. From the above considerations, however, it is seen that another way to diminish the risk of breakdown would be to increase the capacity of one turn to the next, so as to allow

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Mr. Irwin.

a *capacity* current to flow through the coil from turn to turn, and this is probably one of the reasons that the coil A to which Mr. Rider referred has given no trouble, as not only is the coil arranged for minimum potential between turns, but also the capacity between turns is fairly large, and this capacity diminishes the potential across the first few turns. To still further diminish the potential across the first coil and therefore across the first few turns we could shunt the first coil by a condenser, and this would allow a larger current to flow through to the second coil.

If the condenser were very large the first coil would have no potential across it, and the second would now have the abnormal voltage across it and would break down. If the capacity across the first coil from the switching end was equal to the effective capacity of the second coil to earth, then at the moment of switching on the potential across the mains would be practically equally shared by the first two coils. To make the potential divide equally between all the coils it is necessary to shunt them with condensers, except the one nearest the earth end. For rapid changes owing to their very high impedance the coils act only as one plate of a condenser, the other plate being the case of the machine.

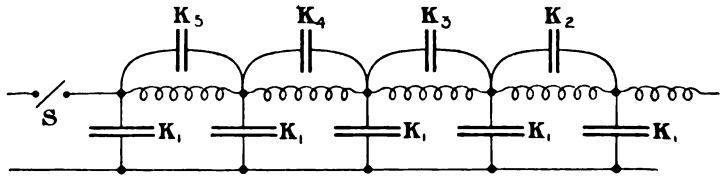

FIG. J.

As shown in Fig. J, K_1 represents the effective capacity to earth of each coil. K_2 is the capacity of the condenser shunting the last but one coil. K_3, K_4, ..., K_5 are the capacities shunting the other coils

It is easy to show that for practically equal potential difference per coil—

$$K_2 = K_1$$
$$K_3 = K_1 (1 + 2)$$
$$K_4 = K_1 (1 + 2 + 3)$$
$$K_5 = K_1 (1 + 2 + 3 + 4)$$

K_1 is a very small capacity as the capacity of a coil to earth is very small, and the effective capacity is much smaller as only a few turns are really effective. I estimate the effective capacity of the coils of the induction motors referred to at not more than 0·0003 of a microfarad. As there are five coils per phase, the largest capacity would be ten times this, or 0·003 of a microfarad. The four condensers required to distribute the potential equally would have capacities of 0·003, 0·0018, 0·0009 and 0·0003 of a microfarad respectively, and

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normally would have to stand a voltage of under 1,500, and even at switching on this should be the maximum potential for each condenser if the grading is correct. This method has the advantage over the choking coil that it can be left permanently connected, as the condenser is of such small size that it could be attached to the coil which it protected, and would therefore safeguard the machine, in normal working, from damage from any rapid change of potential such as that due to a surge or a short circuit. It is very possible that the trouble in some stations due to the deterioration of the end coils is brought about first of all by sparking between the turns owing to line disturbances, and once this sparkling starts it extends, as the pin-hole allows a brush discharge to pass, with the ultimate formation of nitric acid in the winding. Mr Irwin.

The reason an oscillograph does not show the rapid rise of potential is that the frequency of the disturbance is of the order of a million per second, and probably the potential has become more or less equal per coil in the hundred-thousandth of a second. There will not be a simple oscillation of charge in the condensers, as the effective capacity to earth of each coil is altering with time.

Mr. F. H. JACKSON (*communicated*): I should like to offer a few remarks upon the criticisms of Mr. Roberts, of the Post Office, and of Mr. Trezise, his assistant. The calculations made by the latter gentleman are really very extraordinary, and the conclusions arrived at are obviously obtained through starting upon an incorrect basis. I understand that Mr. Roberts is contemplating the use at his new Post Office power station of a straining apparatus of a novel character of his own design, and as yet untried, which it is proposed to fix in the suction of the pumps. It will be interesting to see the result. With the system adopted at Greenwich, where the whole pipe run, including the strainers, is enclosed, and full advantage is taken of syphon action, the head to be dealt with is merely that due to friction, and in such cases a total of 15 ft. is not generally exceeded. This includes the automatic washing of the strainer and the return of all *débris* to the source of supply. Mr. Jackson.

Coming now to actual working results, at Bankside, where strainers are in use dealing with a load of 19,000 k.w., and the circulating pumps are driven by continuous-current motors, capable of speed regulation, it is found possible to carry a 27-in. vacuum on a 4,000–5,000-k.w. load with an expenditure in pumping power of 30 k.w. (a little over ½ per cent.), and this with a large strainer in action capable of dealing with 1,000,000 gallons per hour. As all the water by-passed in this large strainer is included in the pumping, the figures given by Mr. Trezise cannot be correct. In a recent case at an important works the by-passed leakage did not exceed 10 per cent. at ¼ load straining capacity, and at greater loads the percentage is reduced almost in inverse proportion.

In large-sized plants, and where it is desired to deal with heads of considerable amount, we recommend a division of the pumping

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Mr. Jackson.

between two pumps, which can be arranged to balance the pressure across the strainer, thus avoiding all leakage. Mr. Roberts and Mr. Trezise adversely criticise the position of the strainer at Greenwich on the discharge of the pump. Of course, if desired, the strainer could be arranged on the suction, but practical considerations are involved, and I think there can be few who with knowledge of centrifugal pumping (particularly with Thames water, charged as it is with mud and various gases of unpleasant nature) will not appreciate the advantages of a tight suction. Mr. Trezise is also under the impression that the best efficiency is to be obtained by the use of a multiplicity of constant speed pumps of various sizes to suit the load. Our experience at Bankside leads to quite a different conclusion, and I have no hesitation in saying that in practice one or two variable speed pumps will beat the other arrangement every time. It is also an interesting fact that notwithstanding the fancied great defects of the Bailey & Jackson rotary strainer, a large one has been ordered, and is now being erected at the new Post Office power station, and although so adversely criticised in advance, it will, I venture to think, after actual use, meet with the same appreciation there as in other large works.

Discussion at Dublin, April 8, 1909.

Mr. Brew.

Mr. W. Brew: In Figs. 29 and 30 the author gives wave-forms taken between phases and between phase and neutral. These wave-forms differ considerably, and it is evident that a pronounced third harmonic exists in the wave from phase to neutral, whereas the wave between phases appears of nearly sine-form. I would like to ask the author if he has analysed any of these wave-forms, and whether these curves were traced or photographed? I may say that under some conditions with traced curves one finds evidence of a third harmonic in the wave between phases. This may possibly be accounted for by experimental errors, although if the amplitude and wave-form of each phase voltage of the generator was not precisely the same, one might get evidence of a third and other odd harmonic between phases.

I should also be interested to know what were found to be the approximate values of the circulating currents attributed to the presence of odd harmonics in the wave-form. Harmonic analysis of some wave-forms in common use shows that the amplitude between phase and neutral of the third harmonic may be 20 per cent. of that of the fundamental wave, or the effective voltage of the third harmonic may be approximately 1,300 volts, with a voltage between phases of 6,600 volts. Now the impedance of one phase winding at the fundamental frequency will vary with the size and type of generator, and may be anything between, say, 4 and 10 ohms. If we assume an average combination of plant, consisting of generators with irregular wave-form paralleled with another generator with a sine wave, it is probable that the combined impedance of the path taken by the triple-frequency currents would not be less than 5 ohms at the fundamental

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frequency; but there is undoubted evidence that the impedance will not be three times this amount at the triple frequency. If, in the absence of experiment, we assume a value of 10 ohms, we see that we might expect circulating currents of the order of 130 amperes between the machines. Mr. Brew.

There is a further effect not referred to by the author, which has in some cases caused trouble where we have electrical plant subject to a uniform turning moment in combination with other plant subject to an irregular angular velocity. For instance, if we have a large motor-generator in a sub-station and a reciprocating engine in the generating station, it may happen that the natural period of phase swing of the rotor of the motor may coincide more or less with the crank irregularity of the engine. In such cases an alternate transfer of energy results, causing an objectionable surge upon the circuits. In the Greenwich station turbine-driven alternators are paralleled with alternators driven by reciprocating engines, and a phase surge is likely to be set up at heavy loads, causing more or less surging upon the circuits. It would be interesting to know whether Mr. Rider has experienced trouble from this effect.

With regard to the practice of earthing one generator only, the apparatus described by the author is certainly ingenious, and it is obvious that machines differing in wave-form can be paralleled by this method, which would otherwise cause trouble with their neutral points connected up solid. There are one or two difficulties, however, which strike me in connection with this apparatus. The first is (if I understand the working of the switch correctly) that for some interval between the shutting down of the earthed machine and the reconnection of another running machine, the neutral points of all the generators would be insulated from earth. The effect of this would probably not be of so much importance in Mr. Rider's case, because the neutral point of each generator is, I understand, highly insulated; but in those cases where instruments are connected direct in the phase windings at the neutral points, I think it would prove a serious objection. If we supposed also this system of earthing applied to a station in which generators of widely differing outputs are installed, say, between 500 k.w. and 5,000 k.w. output, the phase winding of the small generators might have too large an impedance to open a feeder relay switch on fault, whilst the impedance of the large generators might be unnecessarily small. However, as the length of feeders will vary considerably, no great refinement in keeping the fault current within a definite limit is necessary. Looking at the apparatus from the point of view of simple earthing devices which have been in use up to the present, it seems somewhat complicated and costly; but existing pilot switches and other gear have been utilised in its installation, and have possibly rendered it as cheap an arrangement as could have been adopted.

An alternative in Mr. Rider's case would have been to reconstruct the pole-tips of some of the existing generators to render the wave-form

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Mr. Brew. of each approximately the same, which would undoubtedly have been more costly. The objects to be aimed at in earthing in such cases are:—

1. To maintain the correct relative potential to earth of each phase of the system under normal working conditions.
2. In case of a fault, to restrict the current through the fault to that sufficient to clear the faulty feeder.

I am strongly of the opinion that for this purpose a choking coil or transformer combination could be designed for any given set of conditions without proving too expensive as regards first cost, and it would possess the advantages of simplicity, permanent earthing, and a fixed limit for the fault current.

Mr Tatlow. Mr. W. TATLOW: I should like to point out the very favourable results obtained with the 3,500-k.w. sets in regard to power required for excitation and for driving the auxiliaries. The 50 k.w. provided for excitation represents only 1·4 per cent. of the full output, and the power expended on the air pumps and feed pumps amounts to approximately 1 per cent. and ½ per cent. respectively of the full output. The ingenious arrangement provided for keeping clear the screens on the intake pipes for the condensing water is somewhat similar to a device invented by the late Lord Rosse and used in connection with the water turbines at Birr Castle. A revolving cylindrical screen with a vertical axis is used, a small portion of the water being allowed to escape through a by-wash and traversing the screen in the reverse direction so as to carry away all material caught on the screen.

By combining the results of the trial tests on the boilers and engines given in the paper, we arrive at a fraction over 2 lbs. of coal per unit generated. The figure 3·1 lbs. per unit delivered to the sub-stations is given as the result obtained under actual working conditions. This seems very good, seeing that it covers standby losses, power used in auxiliaries, and losses in transmission. I suggest that in the case of a steam turbine station, where there is no oil in the condensed water, the make-up feed water should be evaporated in special low-pressure shell boilers, and introduced as steam into the low-pressure portion of the turbines. The water in the high-pressure water-tube boilers would thus be maintained practically pure and the blowing down of these boilers obviated. Owing to the good return obtained from low-pressure steam in turbines, the slight loss in efficiency would be more than covered by the saving obtained by not having to blow down the high-pressure boilers, and by the improved evaporation due to absence of scale or sediment in them. The idea of running up the short-circuited rotor induction motors of the motor-generators from the direct-current side is a very good one, as, except in the matter of starting, the permanently short-circuited rotor is vastly superior to a wound rotor with slip rings.

Mr. Porte. Mr. A. C. PORTE: I would like to inquire if the author has had any trouble with the contact plugs on the wharf and the connection

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between them and the cranes. The apparent anomaly in the figures given for calorific values of coal on pages 241 and 244 referred to by Mr. Gill are no doubt due to the tests having been taken before the standard of 12,500 B.Th.U. was set. In my opinion, the results given on page 244 are very good indeed, and with coal of 12,500 B.Th.U. would be better still, say, 10·5 lbs. of water evaporated per lb. of coal and others in proportion, the advantage of the higher calorific value being shown in the reduction in power required in auxiliary plant. The author's method of purchasing his coal on the calorific value, and his code of rules for the merchant's guidance and protection are excellent; the simple method of weighing is also worthy of note. In fact, so far as I have been able to study the author's description, I have found the true engineer's fundamental rule of simplicity with efficiency everywhere evident, and I very much regret that lack of time has prevented me from entering more fully into its discussion. Mr. Porte

Mr. J. P. TIERNEY: I agree with the remarks of Mr. Sheardown as to the great practical value of the paper, and consider the Greenwich station an excellent example of the good results to be obtained by having, when possible, the station designed by the man who is to be responsible for running it afterwards. The adoption of link connections at the back of the street feeder pillar slabs is a very wise precaution against the damage consequent on the closing of wrong switches; also the testing panel in the sub-stations, to enable the rapid localising of a fault on the conduit, is very necessary, and is well designed. If possible I would like to have fuller details of the arrangement for cleansing the circulating water for the condensers. Mr. Tierney.

Mr. P. S. SHEARDOWN: This paper contains a straightforward description of a system designed on a basis of maximum simplicity. Not only is this idea of simplicity in design put prominently forward in the paper, but it is also very noticeable on a visit to the Greenwich station. This simplicity of design is probably due to the fact that the designer of the station is the engineer responsible for its operation. It is only the engineer who has had many years experience of station running who realises the advantage of having not only the apparatus but its grouping and connections as simple, and their use as obvious as possible. When trouble occurs in the station the length of time taken in rectifying it is often due to the difficulty in ascertaining exactly where the fault is and the extent to which the trouble cripples the system, and if this occurs in a box of mysteries which few in the station understand, the length of time during which a system or section of a system is shut down is often much greater than it should be. Mr. Sheardown

The results obtained in the boiler tests after six months' running are good, and, as the author points out, are probably due to the large space for combustion before the gases come into contact with the tubes; and although a large combustion space has been known for a long time to be correct, it is remarkable that this knowledge has not sooner come to be applied to everyday practice. With regard to CO_2 recorders, these are useful assistants, and would well repay the necessary skilled

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Mr. Sheardown.

attention which they require, but rarely receive. With regard to water purifiers, the speaker has obtained excellent results from the Davis-Perrett system of treating the water with a current of electricity which causes the small particles of oil to coagulate so that they can be filtered out by an ordinary self-cleaning sand filter. The advantages of this method are that no chemicals are added to the feed water, and the flow of purified water is always under observation. With reference to the re-heating of steam in the receiver, some tests made by the speaker on a compound Corliss engine appeared to prove that the increase of efficiency in steam consumption used in the cylinders was just counterbalanced by the live steam used in the heating coils. The Parsons vacuum augmentor is a simple arrangement by which the vacuum obtained with any given size condensing plant can be much improved, the principle being to recondense the vapour of condensation as it passes from the main condenser to the air pump, thus increasing the capacity of an air pump of any given size. With reference to the automatic earthing arrangement for the central point of the generator windings, the author appears in this case to have departed from the basis of maximum simplicity, and to have installed what gives one the idea of a complicated apparatus to perform a very simple duty.

Mr. Rider.

Mr. J. H. RIDER (*in reply*): I am much gratified at the lengthy discussion to which my paper has given rise, but I am sorry that there was not time for me to reply at the meeting, as I would much preferred to have said what I have to say before the members than to have given it in writing, with the prospect that my remarks will be read after the interest which was aroused by the paper has subsided.

I do not intend to deal with each speaker in turn, but rather to reply to the remarks under various heads. I will first deal with the question of the change of site for the generating station from Camberwell to Greenwich, a matter which was touched upon largely by Mr. Roger Smith.

It is not surprising that Mr. Smith, who was associated with Messrs. Kennedy and Jenkin, the consulting engineers to the Council at the time, should feel somewhat strongly upon the matter of the change of site, which I was instrumental in arranging so soon after I was appointed to my present post, but I can assure him that I was not concerned so much with the feelings either of the consulting engineers or of myself as with the fact that I was convinced the proposed site at Camberwell was an incorrect one, and that it was my duty to my employers to advise them to make a change.

I think Mr. Smith, in his remarks, missed the real point, as I did not make any comparison whatever between the Greenwich site and the site of his station at Park Royal. My comparisons were rather between the Greenwich site and the site at Camberwell. Mr. Smith asks if I consider the change to have been justified by the results, and my answer is most distinctly, Yes. At the end of his remarks he has added a paragraph asking me what I have done with the 3s. per ton alleged to be saved on coal carriage. If Mr. Smith will refer to the last

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published balance-sheet of the London County Council Tramways, he will see the saving as part of the net profit shown on the tramways undertaking. If it had not been for the saving on coal carriage, that net profit would have been so much less. Mr. Rider.

Mr. Smith appears to argue that because he can obtain coal at Park Royal at a price comparable with that which we have to pay at Greenwich, the change from Camberwell to Greenwich was not justified. I do not find any fault with Park Royal as a site for a station for the Great Western Railway service, as it is on their line, and he has all the facilities which their big organisation can give him in the way of coal carriage, etc. But such facilities were non-existent at Camberwell. Does Mr. Smith remember that it was proposed to build a railway siding from the South-Eastern and Chatham line on to the Camberwell station site, and that the railway company made a stipulation "that the use of the siding should be restricted to three hours in the night-time"? (see London County Council Minutes, July 16, 1901). How much would this restriction have added to the cost of the fuel, and would it have been physically possible to have dealt with a station requiring 150,000 tons of coal per annum if the coal could only be brought on to the site for three hours out of the twenty-four?

I have never argued that a river site is necessarily the best for all generating stations, as everything must depend upon the kind of service which the station has to perform, and the area which it has to serve. If I wanted to build a station for the lighting of my house at Herne Hill, I should put it in the coal cellar, and not on the River Thames. If Mr. Smith wants a station for lighting the Paddington Railway Station, and for a supply in the immediate vicinity of that place, he has probably done quite right to place it at Park Royal; but for a station to supply the tramways of the London County Council, of a size such as we now have, there is, and can be, only one proper place, and that is on the banks of the River Thames.

I am quite content to leave this issue in the hands of my brother engineers, as I am sure that they will agree with my arguments, and I particularly wish to thank Mr. Ferranti for the opinion which he expressed in his remarks—that it was a great achievement on my part to have been able to alter the arrangements of the London County Council, and to persuade them that they were not doing the right thing by building the station at Camberwell.

The difference in the cost of carriage of coal at 3s. per ton between Camberwell and Greenwich was given after I had obtained a number of particulars from large coal merchants. I have just confirmed them by a letter from the largest coal merchants in London, who tell me that if they had to deliver Scotch coal in truck at Camberwell, the cost would be 2s. 3d. per ton more than for Scotch coal delivered at Greenwich, and this on the assumption that the facilities for unloading would be equally good at Camberwell. Mr. Smith is using Midland coals at Park Royal, and I am aware that Scotch coal would be out of the question in his case, as the carriage would be prohibitive. I am able, with a river

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Mr. Rider.

site, to obtain coal from a very much larger range of coal-fields than can Mr. Smith at Park Royal, as the South Wales coal-fields, the Yorkshire coal-fields, and the Scotch coal-fields are all practically equally accessible.

The other facilities which the Greenwich site gave over the one at Camberwell in the question of condensing were not touched upon at all by Mr. Smith. If we had remained at Camberwell, we should have had to use, as pointed out in the paper, either cooling towers or non-condensing engines. The extra coal consumption in the latter case would have been very great, while the use of cooling towers would have most certainly proved a public nuisance, and probably resulted in an attempt to obtain an injunction. I doubt very much whether the site at Camberwell would have been large enough to have contained cooling towers sufficient for dealing with the cooling of about 22,000,000 lbs. of condensing water per hour. If such cooling towers had been used, there would certainly have been no room for the station.

As I stated before, I am not quarrelling with the choice of the site at Park Royal for the use of the Great Western Railway, but I cannot accept the figure given by Mr. Smith of 0·2181d. per kilowatt-hour delivered to sub-stations, because such figure refers only to two months' work, and we can all get good figures if we only take a period short enough. I can give much better ones than that for Greenwich, but I would prefer to discuss Mr. Smith's costs when he will read a paper before the Institution on his own station, and will give details in it as fully as I have done in my paper.

Mr. Smith appears to object to water carriage of coal, and as he is the loyal servant of a large railway company, I can quite understand his position. The old fable is still true, "There is nothing like leather"!

Mr. Salter is of the opinion that a great saving would have been made in the capital expenditure on the transmission system if the generating station had been placed somewhere in the neighbourhood of Southwark. I am glad he agrees with the use of a riverside site, but I am afraid that he does not know London very well, or he would realise not only that a site in Southwark on the river would make the station very objectionable because of its proximity to the City, but also that any saving on transmission cables would probably be more than counterbalanced by the extra cost of the coal, considering that such a site would be above several of the London bridges. The Greenwich station is not so much out of the centre of the system as some people imagine. It must be remembered that, although in the east of London, it is 4 miles westward of the lines in Abbey Wood which we are now supplying.

Notwithstanding Mr. Andrew's criticisms of the Greenwich figures, I am glad that he agrees with me that at the time the Greenwich scheme was proposed there was little to choose between it and an inland site. In view of Mr. Andrews' well-known partiality for gas-engine inland stations, I may take this as being a compliment.

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Mr. Rider.

I come next to our pier arrangements. Mr. Martin Roberts considers that the use of a live rail at 550 volts on the pier is rather dangerous where sailors and others will land from ships. I would remind him that we do not give any landing facilities to the crews of vessels over our pier. I was unable to use overhead wires for the locomotives because they would have interfered with the swinging of the jibs, and the conduit system was out of the question. No trouble has been experienced with the contact plugs and connections to the coaling cranes.

I am sorry that I have given credit to the wrong person for the design of the safety gear for the coal conveyers. I had not seen the particular arrangement we have until it was introduced to me by Messrs. Spencer & Co., but I am glad to know that other people had used it and found it successful.

The conditions of contract which we are able to obtain with our coal merchants were apparently of great interest to the members, and I am very glad of this, as I believe we were the very first to get them put into practice, at any rate on a large scale. I quite agree with Mr. Sparks that once the coal has been taken from the ship into the bunkers it is a very difficult matter to reject it, but we must reserve such a power in the contract, or the coal contractor would have us entirely at his mercy.

Mr. O'Brien asks the size of the coal used at Greenwich. The peas measure from $\frac{1}{2}$ in. to $\frac{3}{4}$ in. I am glad to note that he is able to obtain washed coal with less than 10 per cent. of moisture. By giving the contractor that figure as a basis, he is rewarded in the price by anything better which he can do, and, in my experience, I have not found 10 per cent. to be an improper figure as a basis.

Mr. Patchell remarks that the use of washed nuts restricts the class of coal. I quite agree that this is so, but washed coal has very many advantages, and so far we have not found any difficulty in getting the kind of coal asked for.

Coming next to the boiler plant, Mr. O'Brien thinks that 25 per cent. spare is too much. I do not agree with him, because to get the best results from one's boiler plant the boilers must be kept in the pink of condition. When we remember that the tubes have to be frequently cleaned, the brickwork and the grates frequently repaired, and that the Boiler Insurance Inspector makes periodical visits, it will readily be seen that three boilers out of every four are quite sufficient to have under steam at one time. It must also be remembered that something like 80 per cent. of our working costs is expended on coal alone, and that, therefore, we cannot afford to let the boilers run such a length of time without thorough cleaning, as would in any way increase the fuel consumed per lb. of water evaporated.

Mr. Patchell asks whether the figure of 3,320 sq. ft. given on Table II. of the paper includes the heating surface of the super-heater. It does not. He is of the opinion that our boiler units are too small, but he must not forget that I was handicapped in this matter by the

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Mr. Rider. fact which I mentioned early in the paper, that tenders were let for the first set (16) of boilers, before I was appointed, and that this set the pace for me, at any rate in the first section of the station. The Babcock boilers, which have since been erected, are considerably larger than the original Stirling boilers. Larger boilers than those we now have would have required greater head-room, and so have increased the cost of buildings preceptibly.

In reply to Mr. Clark, the water in Table. II. was measured by means of calibrated tanks. I should be glad if he would publish complete figures of the working of Lot's Road Station for comparison.

In his remarks on our steam-pipe system, Mr. O'Brien thinks that the separators which we use are an unnecessary expense, and he asks how much water is collected in them. I do not agree with him that they are unnecessary, although we do not, under our present conditions of working, get a large quantity of water. In my opinion, success with a steam-pipe system can only be assured by making provison for large quantities of water, and then super-heating to ensure that no water is ever formed. This may be considered somewhat extravagant, but, in our case, has been warranted by the results.

I am somewhat surprised that more remarks were not made concerning our arrangement of reciprocating engines with the high-pressure cylinder vertical and the low-pressure cylinder horizontal, working on a common crank pin. I was much criticised by an anonymous writer when the design was first published, but my experience has been that they are without question the best type for a reciprocating engine of large power. We can start up without any previous preparation, and have the alternator synchronised and in parallel on the busbars at any time under 5 minutes, which is, I think, a good performance.

Mr. Sparks thinks that a speed of 94 revs. per minute is too high for Corliss gear, but this must depend somewhat upon the design of the gear. Certainly a lower speed is usual, but this would have increased the cost of both engine and generator considerably, and I have not found that the speed we have adopted is in any way too high for the satisfactory operation of the gear under all the conditions of load.

Mr. Sparks asks why we adopted 6,600 volts and 25 cycles for the main transmission system. The voltage was adopted as being low enough to get rid of many of the electrical troubles which have been experienced at higher pressures, while still high enough to give satisfactory economy over the area to be supplied. I do not consider one should take into account only the extreme distance of the area in deciding upon the voltage. One should take the load density in the various parts and endeavour to get a voltage suitable for the most economical transmission to the average distance, average here taking into account both distance and density of load.

Mr. Sayers criticises the use of 6,600 volts as being too low, because we happen to have a feeder which is 10 miles long. I think he should, in fairness, have mentioned the fact also that we have some feeders

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which are only 1 mile long, and have argued therefrom that the voltage which we have adopted is far too high for efficient transmission to such a short distance. Mr. Rider.

Mr. Patchell asks why the reciprocating engines were ordered with a power factor of 94 per cent., and the turbo generators with a power factor of 85 per cent. The answer is merely that experience showed the lower power factor to be the one most likely to be reached in actual work. The power factor on the plant, as a whole, is, at full load from 90 per cent. to 93 per cent.; at half load from 80 per cent. to 85 per cent., and at light load during the night-time about 70 per cent. This answers a question also asked by Mr. B. Jenkin.

I agree with Mr. Bailey in his remarks as to the great loss of heat when blowing down the boilers, and am interested to hear that there is a method of removing the oil from the condenser water which will obviate the water becoming too alkaline. I have never heard, however, of the barium alumina process mentioned by him, and should be glad to receive further particulars of it. Of course the blowing-down difficulty does not exist when we are dealing only with turbines, as no oil is used with the steam, and, therefore, when the Greenwich station is fully equipped, and the reciprocating engines form only a comparatively small proportion of the total plant, the trouble will have much diminished.

Mr. Patchell asks as to the level of the water in the artesian well tube as compared with Ordnance Datum. The top of the tube is 5·88 ft. above Ordnance Datum, and the level of the water being 5 ft. below the bottom of the tube is, therefore, about 0·88 ft. above Ordnance Datum. Replying to him also, the Kennedy water meters are on the delivery side of the boiler feed pumps, but although these meters are the best so far that I have been able to obtain, they are still very unsatisfactory, and frequently allow so much water to pass without measuring it, that for some time I have given up the use of any meters at all. I am now considering whether it will be possible to use a modification of the Lea recorder for this purpose.

Mr. Martin Roberts asks if we have found any economy in the use of turbines over reciprocating engines. After taking into account the extra losses in the auxiliary plant, such as the amount of power used for pumping the condensing water, etc., I am pleased to state that we have found considerable economies, not necessarily because the turbines are in themselves more economical than reciprocating engines at certain loads, but because their characteristics have enabled us to get the best result from both them and the reciprocating engines. That is to say, last year, the year for which the figures were given in my paper, we had to work the reciprocating engines largely on overload, with the result that the steam consumption per kilowatt-hour was excessive. This year, however, we are able to put a heavy constant load on the turbines, to work them at their most economical point, and to use the reciprocating engines for filling up the hollows, keeping them at their most economical point also, *i.e.*, at about three-quarters

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Mr. Rider.

of full load. No trouble whatever is experienced in running the turbines and reciprocating engines in parallel. The coal consumption per unit delivered to sub-stations has decreased by something like 20 per cent. since the beginning of 1909.

Mr. O'Brien asks some questions with reference to the clearances in the Willans turbines, and I have pleasure in giving the following particulars :—

Radially between rotor blades and casing, between 0·033 in. and 0·162 in.

Radially between stator blades and shaft, between 0·040 in. and 0·151 in.

Axially between rotor blades and stator blades, 0·2 in.

These clearances were measured cold, as I have not been able to arrive at any satisfactory means of measuring them hot.

The impulse turbine was not adopted for the other two turbine-sets now on order because I hoped to obtain any more reliability with them on account of larger radial clearances, and I am not able to say what the effect of blade erosion may be, but I hope to be fully informed on these and other points in connection with impulse turbines in the course of a year or so.

Before dealing with the remarks on the Greenwich switchgear, I wish to point out an error which has crept into Fig. 14 of the paper. This was pointed out to me by Mr. Frank Walker immediately my paper was published, but unfortunately it was too late to make the correction in the figure. Mr. Clark drew attention to this mistake in his remarks, and it is that the static transformers are shown as being fed by duplicate feeders coming from the same section busbars, and the local sub-station at Greenwich is shown as being fed in the same manner. This is a mistake in the diagram, as both the static transformers and the local sub-station are fed with their duplicate mains coming from independent busbar sections. In fact, throughout the whole system, those sub-stations which would be dependent upon one another for a supply in case of failure of any main feeder are fed from independent busbar sections.

A considerable amount of interest was shown, not only in the discussion, but afterwards in the technical papers, in the automatic earthing switchgear which I described, and I am afraid there is a little misconception as to the size of the gear, its complication, and its cost. Several speakers referred to the fact that in their particular stations no cross-currents between machines were noticed, and that, therefore, there was no need for a device which would only earth one machine. This is hardly the point, as the real value of earthing only one machine is to limit the effect in the station of an earth on the mains outside. If all the machines are connected together to a common earth, the effect of an external earth is to bring down the voltage of the whole station pending the opening of the circuit breaker on the faulty feeder. In our case the effect is only felt on one machine, and since this earthing

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resistance has been in use at Greenwich it has been most beneficial for this reason. Mr. Rider

I am sorry that the illustration of the earthing switch in Fig. 19 did not give any idea of its dimensions. It is, however, quite a small affair, and measures only 30½ in. long × 22 in. wide × 22½ in. high, and its cost was under £50. This does not, of course, include the cost of the resistance itself, which was built up of cast-iron grids similar to the resistances used on the cars.

The machines are left unearthed during the short interval in which the automatic switch is revolving after one machine has been shut down. This interval, however, is only for 2 or 3 seconds, and the risk of any accident happening outside at that time is so remote as to be entirely negligible. If an earth did take place during switching operations the closing of the automatic earthing switch would only have the same effect as though the earthing switch had been previously closed, and the earth had come from outside afterwards.

Mr. Brazil raises an interesting point, which is that if we run the Greenwich station with the busbars divided only one of those bars would be earthed by the automatic switch. This is quite correct, but as the dividing of the busbars would only be done in the unlikely event of being unable to run in parallel for some unknown reason, we should close the earthing switch on one machine on each side by hand and cut out the automatic apparatus for the time being.

I am not competent to enter into a discussion as to the relative advantages of ohmic resistances, inductive resistances, or combinations of the two for use in earthing machines, as I am content to know that the earthing apparatus we are using at Greenwich is most effective and satisfactory. I was interested, however, to read in one of the technical papers a short time ago an article deprecating the use of inductive resistances for earthing machines.

Mr. Brazil asks for information regarding the working of the spark-gaps, but I regret that I am not able to say how these operate, as so far as I am aware we have had no rises of pressure sufficient to bring them into use. Mr. Forrest asks if the spark-gaps ever operated before the star-point was earthed at the generating station. The star-points have always been earthed, as is clear from the paper, and I therefore cannot understand the object of his question.

Mr. Clothier's remarks on the switchgear at Greenwich and his alternative design are very interesting. I hope it will never be said that finality has been reached, and certainly Mr. Clothier's design shows that even the Greenwich switchgear, which, when it was designed, was as simple as was then known, can be made still simpler. I am very glad that he is working towards simplicity in design, because, in my opinion, a simple apparatus is one which will be far less likely to go wrong than one which is more complicated.

Mr. Snell asks why we place the switch cells on the third gallery. There would have been no saving of cables to have placed them on the ground floor unless the isolating plugs and trifurcating boxes had

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Mr. Rider.

been there as well. The idea was to get the cells, with their switches, well out of the way, where they would not be likely to cause trouble if anything should happen.

Mr. Trezise asks for further information respecting the arrangement of the Greenwich switchgear. We use insulated handles for the isolating plugs as a double precaution. Wooden tongs are used to pull them out, although, in my opinion, it will be quite safe to handle them. We do not use the ordinary pattern of knife switch with hook, because it is not nearly such a mechanical job.

Mr. Edgcumbe made some interesting remarks on the use of reverse-current relays. On two occasions when our relays should have acted they failed to do so, and in one case fortunately for us. In one case the shunt circuit of an exciter was accidentally broken while the machine was on the busbars. The relay, however, did not open the circuit. In the other case the automatic stop valve on one of the reciprocating engines was accidently tripped, cutting off all the steam from the engine. The engine merely motored, and the attendant was able, by gradually opening the automatic valve, to put full load on the generator again without in any way interfering with the supply or disconnecting the machine.

As the whole aim of the station should be to maintain an outside supply under all conditions, I think we should rely upon nothing but a hand-operated switch for pulling a machine out of circuit in the event of a failure of the machine itself, and not allow any automatic apparatus to be capable of doing so. Automatic apparatus frequently fails to operate at the critical moment, and the simpler one can make the switchgear of a large station the better.

Mr. Salter criticises the use of storage batteries at Greenwich, but if he will read the paper again he will see that their great use is as a standby for the power and lighting circuits of the station, for the operation of the switchgear, and, when necessary, for the boiler feed pumps. Their use in this manner is entirely justified, but with our load factor could not be justified for the sub-stations.

Coming next to the remarks on our condenser water arrangement I was interested in the little duel between Messrs. Bailey and Roberts. Each being the designer of a rival strainer, it was natural that each should be able to see points of demerit in the other's design.

Mr. Bailey, however, is incorrect in stating that the leakage of 15 per cent. across his strainer at Greenwich is due either to a high head of 30 ft. or to the pipes being too small. I give below the figures of some tests made on November 26, 1907, and some further tests made on March 30, 1909, from which it will be seen that although the head on the pump may be higher than 30 ft., the highest head we have measured on the strainer, *i.e.*, the difference of pressure between the inlet and outlet sides, is only 19 ft. It must not be forgotten that we have to provide a head of at least 10 ft. across the inlet and outlet on our turbine condensers, and to do this at the end of an engine-room 400 ft. long means a higher head in the pump house.

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Mr. Rider.

From recent experience with the Bailey rotary strainer we have found the leakage increasing, and are now endeavouring to adopt some easy means of taking up the wear on the strainer wheels, so as to bring the leakage down to an adjustable minimum. I see that Mr. Jackson recommends the use of two pumps in series, one on each side of the strainer, so as to reduce the head on the strainer itself, but this will complicate matters very considerably.

Mr. Trezise asks how much water is used for sealing round the strainer wheel. I regret that I cannot tell him, as it is taken by a small pipe from the tank on the pump-house roof, and I have no means either of measuring it or of knowing what it costs. I shall be very interested to see the result of the working of the Roberts

TESTS TAKEN ON BAILEY AND JACKSON ROTARY STRAINER.

Gallons per Minute.	Pressure on Strainer.		Actual Head across Strainer.	
	Flow.	Return.		
November 26, 1907:	Feet.	Feet.	Feet.	
13,000	44	28	16	Supplying condensers of reciprocating engines.
13,420	43	28	15	
13,450	43	27½	15½	
13,600	47	31½	14½	
March 30, 1909:				
10,000	34¾	15¾	19	Supplying condensers of turbine.

strainer at the Post Office station as soon as that station is really ready.

Mr. Roberts asks if the barometric pipes are of any use, and Mr. Clark inquires as to the Venturi water meters and the vacuum which the air pumps maintain for the barometric pipes. If the barometric pipes are placed in the right position, *i.e.*, at the highest points of the delivery system, they will be effective. Each Venturi meter will pass about 12,000 gallons per minute, and the vacuum at which we work on the barometric pipes is about 25 in.

Mr. Partridge has criticised the use of alternating-current motors for driving the centrifugal pumps, and until we had adopted the system of earthing only one generator we had occasional trouble due to the slowing down of these motors when a heavy short took place outside. Since we made the alteration in the earthing resistance we have had no trouble whatever, and the simplicity of the motors is a great point

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Mr. Rider.

in their favour. We have been running our present motors for over three years without the slightest hitch or trouble due to the motors themselves, and I think their advantages from the point of view of simplicity are very much greater than any possible disadvantages, particularly when the trouble caused by the brush-gear and commutator of a direct-current motor is taken into account.

Mr. Patchell asks how much condensing water we use for the turbines. We are using about sixty times the weight of steam, which is, of course, an amount considerably in excess of that needed for the lower vacuum necessary for reciprocating engines.

Mr. Patchell congratulates me with having returned to normal ways of thinking in rating my plant on its normal capacity and not on the Parliamentary capacity. If he will refer to the tables which I presented to Committees of the House in 1906 and 1907, on behalf of the London County Council, he will see that I always gave the output of the stations in terms of their normal or rated capacity. He must be mistaking me for some other distinguished engineer!

The remarks which were made about the sub-station plant were exceedingly interesting, and raised a number of important points. Mr. Jenkin asks why I did not mention more difficulties than those with piston rings and coil failures of motor-generators. The answer is, because we have had no difficulties to speak of other than these. I agree with him that spark-gaps properly adjusted may be used to show rises of pressure on the stator coils, but they are not the best kind of things to be experimenting with on a live tramway system.

Several speakers asked why I did not use rotary converters. The answer is, simply because I considered motor-generators to be more advantageous for our purpose. I realise that there are advantages and disadvantages in both types of machines, but it seemed to me, with the experience at my disposal when our designs were first got out, that the motor-generator was to be preferred. I really should refer this particular matter to Mr. Hallo, the reader of the next paper, because his answer would be, "Use neither motor-generators nor rotary converters, but La Cour motor converters." As a matter of fact, we have two 1,500-k.w. rotaries now on order.

Mr. Patchell is in error in assuming that we have gone in entirely for induction machines, as, if he will refer to page 273 of the paper, he will see that we have a considerable capacity in synchronous machines.

Mr. Jenkin asks for the relative efficiencies of the sub-stations using synchronous and induction machines. I can only take tests under daily working conditions, but, speaking generally, I find that the sub-stations with induction machines show a higher efficiency. The average of all our synchronous sub-stations is 73·5 per cent., and of all our induction sub-stations 82·1 per cent. This may be due either to the fact that the induction machines are of larger individual capacity, or that the induction machine sub-stations are generally able to run at a higher output per machine than the synchronous machine sub-stations,

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and the figures given should not be taken as being by any means conclusive that a higher average efficiency can be got out of one type of machine rather than another. Mr. Rider.

I am afraid there is a misunderstanding with reference to the figures given on page 273 of the paper, as Mr. Snell thinks that we have made arrangements for 33 per cent. of spare plant in each of our sub-stations. This is not so, as we have nothing like one-third spare plant as a rule. We are generally working on our overload capacity, and frequently up to 50 per cent. overload on the sub-station plant at peak times. The figures on page 273 were merely intended to show that we had sufficient capacity in the sub-stations for the possible plant which could be put into Greenwich.

Mr. Sparks asks about the diversity factor of 1·25. This is not reckoned on momentary overloads, but is taken on the average of the readings of the kilowatt meters.

Mr. Partridge's remarks as to the use of a water resistance for starting up the motor-generators are interesting, and although he has successfully used such resistances for small single-phase motors of 2,000 volts pressure, I should not like to use them for large 3-phase machines at a pressure of 6,600 volts between phases. I think choking coils are much simpler and quite as effective.

I do not agree with Mr. Sayers's suggestion that the breakdowns which we have experienced on the terminal coils of the motor-generators have been caused by any mechanical movement in switching on. The particular experiments which he mentions as having been carried out on certain of our machines were made on an older type by Messrs. Dick, Kerr & Co., Ltd., the coils being hand wound. Such coils have not anything like the stiffness of the newer type, such as are shown in E, Fig. 25, and built to the specification given in the paper. As a matter of fact, we have had practically no breakdowns on motor-generators of the type referred to by Mr. Sayers.

I have not taken any curves of the current rushes on switching in a motor-generator, but I am hoping to do so shortly. In my opinion the breakdowns have been due entirely to the reasons given in the paper—*i.e.*, to the fact that, at the moment of switching on, the busbar pressure is practically concentrated not only on the end coils, but on the end turns of those coils.

It is interesting to note that an engineer of Mr. Sayers's experience does not recommend rotary converters, but I am not able to agree altogether with his recommendation of La Cour motor converters, possibly because I have not myself had experience with them.

Mr. Howe made some interesting remarks, which were, however, more suitable for the college lecture-room than for engineers who have to deal with actual live systems. His suggestion that we should use a series of condensers may be excellent in theory, but would not, I think, prove very efficient in practice. I do not know where we should find room for the condensers, as there is generally no free space about the coils of a machine. All such auxiliary high-tension apparatus should

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Mr. Rider.

be, as far as possible, taken away, and a cure obtained by building the coils of the machines in such a way that they will stand the high pressure to which they may be subjected.

Mr. Salter is evidently of the opinion that the high units per car-mile referred to by several speakers, which I deal with more particularly later, are to be accounted for by the fact that we use shunt-wound machines in our sub-stations. I do not see why he should doubt my word that shunt-wound machines have been and are being used in order to get machines and switchgear of the simplest possible kind. This is the fact, and the simplicity is certainly worth getting, more particularly as the use of shunt-wound machines has not made any practical difference to the pressure regulation of the system.

How the use of a shunt-wound machine can have anything to do with the inherent defects of the conduit system I cannot make out, as such inherent defects are due entirely to the fact that it is a conduit, and have nothing whatever to do with the system of electrical feeding. Mr. Salter is apparently under the impression that our shunt-wound machines regulate very badly, that we have the full pressure of 550 volts only on open circuit, and that as soon as any load comes on the pressure falls very rapidly, with the result that the cars take more amperes to do their work. As a matter of fact, the load at our sub-stations is remarkably uniform, and I am sorry that I am not able to publish a pressure curve. I should, however, at any time be pleased to show Mr. Salter, or any other anxious inquirer in this direction, the working of our sub-stations, when he would see that the use of shunt-wound machines does not materially affect the pressure on the conductor bars in the conduit.

Several speakers drew attention to the fact that the units per car-mile taken by the London County Council cars were much greater than those in other cities, notably Glasgow, with which we were unfavourably compared. No comparisons or figures of this kind were given in the paper, but I have no objection to dealing with them, as I think they are very interesting.

In speaking of units per car-mile, one is bound to ask, in the first place, what is meant by the term "car-mile." No fair comparisons can ever be made of the energy taken by the various tramway systems unless the whole of the circumstances are known and are taken into account. The published returns of tramway undertakings state the units per car-mile, without any reference (*a*) to the places or points where the units are measured, (*b*) to the weights or speeds of the cars, or (*c*) to the character of the roads. In a return for the year ended March 31, 1908, in a leading tramway journal, the figures for some 78 undertakings are given, and the units per car-mile varied from 0·953 to 2·24, a difference of no less than 135 per cent. Such returns are not only of no value—they are distinctly misleading.

The electrical energy may be measured at a number of places, depending largely upon the method of production, and whether the tramway authority generates or purchases its energy. For example,

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the meters may be fixed (1) in the cars, (2) in the low-pressure feeder pillars, (3) in the low-pressure feeders at the generating (or sub-) stations, (4) in the high-pressure feeders in the sub-stations, or (5) in the high-pressure feeders in the generating station. Mr. Rider.

Examples of all the above methods could be given from actual practice, and the results obtained from (4) and (5) are frequently rendered more confusing by including the energy used for lighting car-sheds, stations, and other depôts. As a matter of fact, no place at which energy should be measured can be stated as being the correct one, unless it is first decided what is to be included in the measurement, and for what purpose the measurement is to be made.

If the Tramways Department purchases its energy either in the form of low-tension direct current fit for immediate use on the cars, or as high-tension energy which has to be transformed, the measurement will usually be made at the point or points of delivery from the supply authority. In such cases the measured units would be taken as those to be quoted in the tramway return, and with some reason, but they would not necessarily be correct to be used in comparison with other systems.

The use of the term "car-mile" as a unit of comparison is almost universal in the tramways industry. In the days of horse-cars, when sizes and speeds of cars were practically uniform, it was perhaps as satisfactory a term as could be used, but for electric traction it is, in my opinion, entirely unsuitable.

The power required to drive the car depends primarily on three things—its speed, its weight, and the gradient of the road. In fact, the power is directly proportional to each of the first two, and if either the speed or the weight of the car be doubled, the power required is doubled also. Now, to take the actual figures quoted in the discussion—of Glasgow, 1·25 units per car-mile, and London, 2·24 units per car-mile—I have been able, through the courtesy of Mr. J. Dalrymple, to obtain detailed figures from Glasgow, from which I find that, to make a direct comparison with the London figures, the units per car-mile should be 1·34, as the figure of 1·25 does not include anything for sub-station lighting or for use in car-sheds or depôts. The London figure includes all these items.

The Glasgow cars weigh on the average, with the passengers, 13 tons; while in London the cars weigh, under similar circumstances, 19½ tons. In Glasgow the average speed is 7·93 miles per hour, and in London 8·75 miles per hour. If these figures be worked out, it will be seen that the units per *comparable* car-mile are practically the same in each case.

In my opinion the term "car-mile" should be discarded, and all comparisons between systems should be made by a "figure of merit," or by dividing the results per car-mile × 100* by another figure

* An arbitrary multiplier used to bring the result to a figure similar to the present "units per car-mile."

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Mr. Rider.

obtained by multiplying together the average weight of the cars in tons, and the average speed of the cars in miles per hour thus :—

$$\frac{\text{Units per car-mile} \times 100}{\text{Average weight in tons} \times \text{average speed in m.p.h.}} = \text{figure of merit.}$$

As an example of the application of this suggestion, we may take the figures of Glasgow and London mentioned above, and it will be seen that the—

$$\text{energy figure of merit for Glasgow} = \frac{1{\cdot}34 \text{ units} \times 100}{13 \text{ tons} \times 7{\cdot}93 \text{ m.p.h.}} = 1{\cdot}299,$$

$$\text{energy figure of merit for London} = \frac{2{\cdot}24 \text{ units} \times 100}{19{\cdot}5 \text{ tons} \times 8{\cdot}75 \text{ m.p.h.}} = 1{\cdot}312,$$

or practically the same, without making any allowance whatever for the most important condition, that of traffic obstructions. In London these are much worse than in Glasgow, and the heavier the cars the greater the loss due to frequent starting and stopping to avoid other traffic. On certain of the County Council roads the energy per car-mile is as much as 25 per cent. less on Sundays than that taken during weekdays for this reason alone. After making, therefore, the allowance to London which is only fair under these circumstances, it will be seen that the units per car-mile used are nothing at all out of the ordinary.

I am afraid that I have missed many points raised by several of the speakers, but the length of my reply is already getting as great as that of the paper itself, and I must therefore draw to a conclusion. Many of the points have been answered by others, and if I have unwittingly omitted to reply to any of the points which were specifically asked for, I am sorry, and hope that, at some future date, when the station at Greenwich is completed, and the electrification of the remaining lines carried out by the Council, I may be able to supplement this paper by another one giving the final figures.

I must express my thanks to the members for the excellent manner in which the paper was discussed, and particularly to the Council for having awarded me the Institution premium.

The President.

The PRESIDENT: The pleasant duty now remains to me of asking you to accord a very hearty vote of thanks to Mr. Rider for the paper he has read. It is a long time since we gave up three nights to the discussion of any one paper; but the Council gave the time because it was felt the paper was a very important and valuable one, and that it was of great importance to take the opportunity of eliciting as much information as we could from those who have taken part in the discussion. The author has had a great compliment paid to him by the valuable discussion that has taken place. I wish to thank him personally for contributing the paper. When you did me the honour of making me your President, the first person I went to for a good, practical paper to be read during my term of office was Mr. Rider, and this is the paper. I ask you to accord a hearty vote of thanks to him.

The resolution of thanks was carried by acclamation.

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Proceedings of the Four Hundred and Ninety-second Ordinary General Meeting of the Institution of Electrical Engineers, held in the Rooms of the Institution of Civil Engineers, Great George Street, Westminster, on Thursday evening, April 1, 1909—Mr. W. M. MORDEY, President, in the chair.

The Minutes of the Ordinary General Meeting held on Thursday, April 25, 1909, were taken as read and confirmed.

The list of candidates for election into the Institution was tal en as read, and it was ordered that it should be suspended in the Library.

The following list of transfers was announced as having been approved by the Council :—

TRANSFERS.

From the class of Associate Members to that of Members—

William Brown.
William Buchanan.
Herbert B. Harvey.
Clifford Lakin-Smith.
Herbert W. Umney.

From the class of Associates to that of Members—

Arthur E. C. Burgess.

From the class of Associates to that of Associate Members—

Robert C. Pierce.

From the class of Students to that of Associate Members—

Henry G. Andrews.
John T. Atkinson.
Henry P. Baynham.
Edward Stanley Byng.
Percy James Clears.
Raymond Correa.
A. E. H. Dinham-Peren.
Harold W. Fulcher.
Egerton B. Hunter.
B. Leigh.
Frederick H. Masters.
John Edward Minchin.
Alfred T. Morris.
Graham L. Porter.
John G. Potts.

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From the class of Students to that of Associates—
Joseph Chatwin-D'Horschel.

The adjourned discussion on Mr. J. H. Rider's paper, "The Electrical System of the London County Council Tramways," was resumed (see page 300).

The meeting adjourned at 9.45 p.m.

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Proceedings of the Four Hundred and Ninety-third Ordinary General Meeting of the Institution of Electrical Engineers, held in the Rooms of the Institution of Civil Engineers, Great George Street, Westminster, on Thursday evening, April 22, 1909—Mr. W. M. MORDEY, President, in the chair.

The minutes of the Ordinary General Meeting held on April 1, 1909, were taken as read, and confirmed.

The list of candidates for election into the Institution was taken as read, and it was ordered that it should be suspended in the Library.

The following list of transfers was announced as having been approved by the Council :—

TRANSFERS.

From the class of Associate Members to that of Members :—

William Henry Upton Marshall.	Theodore Schontheil.
	Harold Harman Simmons.

From the class of Associates to that of Members :—

Alexander Davidson.

From the class of Associates to that of Associate Members :—

Allan Arthur.	Edmund R. Spence.
Arthur F. T. Atchison.	John Price Strange.
Percy A. Spalding.	Capt. Richard F. Willis.

From the class of Students to that of Associate Members :—

Randal S. Callender.	Sam Birdwood Reid.
Matthew H. Curry.	Guy Septimus Rose.
Leslie H. Davies.	Thos. Yeo Sherwell.
William Henry M. Parr.	Edward D. Spencer.
Reginald W. Penny.	Ashton L. Trickett.
Thos. Alex. Pudan.	Thos. F. Wall.

Owen John Williams.

Messrs. A. H. Allen and C. W. Smith were appointed scrutineers of the ballot for the election of new members, and, at the end of the meeting, the following were declared to have been duly elected :—

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ELECTIONS.

As Members.

Bernard Price. | William Ryle Wright.

As Associate Members.

Herbert Arthur Brimelow.
George Broadhurst.
Charles Edward Brotherton.
William Anderson Brown.
Alexander Gerald Cuthbert.
Matthew M. McC. Hoey.
Arthur Ineson.
Arthur Cyril Jennings.
James Leadbeater.
Frank B. Leonard.
Leonard Hinchliffe Marlor.
Frederick Disney Napier.
Charles Elliott Fowlds Parker.
Philip Septimus Pitt.
Thomas S. Shenton.
William Sedgwick Stafford.
Herbert Van Dieman.

As Associates.

Basil Condon Battye, Lieut. R.E.
George Christopher Lloyd.

As Students.

George William Flynn.
John Barker Hartley.
John Mould.
Percy Charles Organ.
William Arthur A. Page.
Brij Lal Pasricha.
Frederick H. Stott.

Donations to the *Library* were announced as having been received since the last meeting from B. Blount, W. Duddell, F.R.S., The Engineering Standards Committee, The Gresham Publishing Company, C. Griffin & Co., A. Hands, Professor A. Jamieson ; to the *Building Fund* from W. A. Del Mar, W. McGeoch, jun., N. Tesla ; and to the *Benevolent Fund* from T. H. Minshall, to whom the thanks of the meeting were duly accorded.

The PRESIDENT read the following list of Council nominations for election to the Council for the ensuing Session :—

MEMBERS NOMINATED BY THE COUNCIL FOR OFFICE, 1909–10.

As President.

New Nomination DR. GISBERT KAPP.

As Vice-Presidents.

Remaining in Office COLONEL H. C. L. HOLDEN, R.A., F.R.S.

New Nominations SIR H. H. CUNYNGHAME, K.C.B.
W. DUDDELL, F.R.S
S. EVERSHED.

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As Ordinary Members of Council.

Remaining in Office	DR. E. HOPKINSON.
	J. W. JACOMB-HOOD.
	T. MATHER, F.R.S.
	MAJOR W. A. J. O'MEARA, C.M.G.
	W. H. PATCHELL.
	W. RUTHERFORD.
	J. F. C. SNELL.
	G. STONEY.
	A. H. WALTON.
New Nominations	W. W. COOK.
	G. K. S. ELPHINSTONE.
	W. JUDD.
	W. M. MORRISON.
	J. H. RIDER.
	C. H. WORDINGHAM.

As Associate Members of Council.

Remaining in Office	H. HUMAN.
	J. E. TAYLOR.
New Nomination	E. RUSSELL CLARKE.

As Honorary Treasurer.

For Re-election ROBERT HAMMOND.

As Honorary Auditors.

For Re-election H. ALABASTER. SIDNEY SHARP.

The adjourned discussion on Mr. John H. Rider's paper, "The Electrical System of the London County Council Tramways," was concluded (see page 317).

The meeting adjourned at 9.30 p.m.

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Proceedings of the Four Hundred and Ninety-fourth Ordinary General Meeting of the Institution of Electrical Engineers, held in the rooms of the Royal Society of Arts, John Street, Adelphi, W.C., on Thursday evening, May 6, 1909—Mr. W. M. MORDEY, President, in the chair.

The minutes of the Ordinary General Meeting, held on April 22, 1909, were taken as read and confirmed.

The list of candidates for election into the Institution was taken as read.

The following list of transfers was announced as having been approved by the Council :—

TRANSFERS.

From the class of Associate Members to that of Members—

Charles J. Beaver.	William Johnston.
Sydney E. Britton.	Frederick W. Lacey.
Julius Frith.	Roland Marshall.
William Eversley Hardy.	Charles Mittelhausen.

Theodore Stevens.

From the class of Associates to that of Associate Members—

Ernest Coates.	Ernest M. Martin.
James Fraser.	Thomas A. Mitchell.
Frederick E. Kennard.	Thomas F. Purves.

Robert Alexander Ure.

From the class of Students to that of Associate Members—

Claud J. Elliott.	Henry A. Pickett.
Charles H. D. Lang.	Harry R. Speyer.
Horace H. Leage.	William Gilbert Turner.
William S. Lonsdale.	Mitchell H. Upton.
Herbert Pearce.	Cyril F. Upward.

Bernard P. Walker.

Messrs. W. James and J. H. Johnson were appointed scrutineers of the ballot, and, at the end of the meeting, the following were declared to have been duly elected :—

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ELECTIONS.

As Members.

Professor Comfort A. Adams. | Aubrey Victor Clayton.
Archibald Page.

As Associate Members.

Albert Frederick Coates. | Alexander Paterson Robertson.
William Holmes. | Ernest Morris Outram Scott.
Edward Lionel Joseph. | Stanley Parker Smith.
George Edward Francis Webber.

As Students.

Edward Stephen Coombes. | Vincent Henry Matthew McMahon
John Frederick Daniels. | William Walter Pullen.
Leonard Wallis.

Donations to the *Building Fund* were announced as having been received since the last meeting from J. Kynoch, G. C. Lloyd, F. Tischendorfer, and to the *Benevolent Fund* from L. Birks, and the Building Trades' Gift to the Nation, to whom the thanks of the meeting were duly accorded.

A paper (see page 374) by Mr. H. S. Hallo, entitled, "The Theory and Application of Motor Converters," was read and discussed.

The meeting adjourned at 9.40 p.m.

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THE THEORY AND APPLICATION OF MOTOR CONVERTERS.

By H. S. HALLO.

(*Paper received December* 21, 1908, *and read in London on May* 6, 1909.)

I. INTRODUCTION.

Until the year 1904—as far as this country was concerned—there were only two classes of machines in general use for the conversion of alternating current into continuous current, these being the motor-generator and the rotary converter.

The alternating-current side of the motor-generator may be of the synchronous or of the induction type. In both cases the stator winding may be wound for high tension, but not so with the rotary converter, the additional complication of static transformers being necessary. Though the efficiency of rotary converters in conjunction with static transformers is much higher than the efficiency of motor-generators, and though the initial cost may also show a decided advantage, the rotary converter has made but little headway in this country. This is mainly due to the fact that the great majority of alternating-current plants are designed for 50 ∿ per second, and for well-known reasons the rotary converter is not very suitable for this class of work. For 25-∿ circuits, however, the rotary converter is a serious competitor of the motor-generator, though even in this case each system has its advantages and its limitations.

As stated above, the rotary converter has advantages on the points of efficiency and first cost. With regard to starting up from the alternating-current side, however, the motor-generator—when of the induction type—shows many advantages, there being no skill whatever required for this performance. One might think, at first sight, that the synchronous machine stands on equal footing with the rotary as far as starting is concerned. This, however, is not the case, since with the motor-generator there is no liability of the polarity on the continuous-current side becoming reversed at starting up—a contingency which has often given trouble with the rotary converter, necessitating the use of more complicated switchgear by the introduction of double-pole change-over switches, or other contrivances.

The characteristics and the regulation of the continuous-current side of the motor-generator may be adapted to all requirements, and

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are entirely independent of the alternating-current supply, whereas the direct-current voltage in the case of a rotary bears a constant ratio to the alternating-current voltage, and is affected by fluctuations of that voltage. Of course, it is possible to regulate the direct-current voltage of a rotary within narrow limits by the aid of choking coils or similar means, but for wide regulation of voltage an additional booster is required, which materially affects the simplicity of the plant, the first cost, and efficiency.

The synchronous motor-generator, moreover, is the better machine if reversibility is required. Certainly a rotary is reversible in theory, but as soon as wattless currents are taken from the alternating-current side the rotary shows a tendency to race.

From the point of view of hunting the induction motor-generator is certainly the safer machine, and the synchronous motor-generator is in this respect far superior to the rotary; this has been amply borne out by experience gained on both sides of the Atlantic.

The latter point is especially marked in the case of the 50-cycle rotaries, which, moreover, have the additional disadvantage of a great number of poles, the distance between adjacent sets of brushes thus being small notwithstanding the large diameter of commutator.

There is also the difficulty with these machines of finding room for commutating poles, which have been adopted in recent designs as a necessary adjunct.

From this short summary it will be noticed that it is small wonder the motor-generator, especially for 50-period circuits, held the field in spite of its low efficiency and high first cost.

Since the year 1904, however, a new machine for the conversion of alternating into direct current has been put upon the British market under the name of "motor converter."*

It is claimed that this machine combines the good points of both the other systems, whilst it avoids their defects. It is self-starting, yet runs synchronously when up to speed—the synchronising force being so strong that it is almost impossible for the machine to fall out of step. The characteristics of the continuous-current side may be adapted to any ordinary requirements; its voltage may be regulated by adjusting the shunt resistance, and it can further be arranged as a 3-wire generator, when it will automatically deal with very large out-of-balance currents. There is no possibility of reversal of polarity as with the rotary converter. The efficiency is substantially higher than that of a motor-generator of the same output, and is nearly equal to that of a rotary with its transformers. It is reversible, and even when supplying current to modern induction motors its regulation is excellent. The first cost is less than that of a motor-generator, and when a large voltage variation is required the motor converter works out considerably cheaper even than the rotary, alternating-current boosters being necessary with the latter machines in such circumstances. Furthermore, the motor

* This machine was patented by Messrs. J. L. la Cour and O. S. Bragstad in the year 1902.

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converter takes up considerably less floor space than either of the former types of converting plant. This statement is borne out in practice, as there are several installations where, by the adoption of motor converters, plant of considerably greater capacity has been put into the space available than would have been possible with either of the previous types.

Under these conditions one cannot wonder that the motor converter has made such rapid headway, and that by this time almost two hundred converters, with an aggregate capacity of over 80,000 k.w., have been installed. Seeing that the motor converter thus plays such an important part in modern sub-station practice, and that the literature on the subject is very scarce, the author of the present paper trusts that a short explanation of the principle, operation, design, and characteristics of this interesting machine may prove acceptable.

II. Principle.

The motor converter consists of an ordinary induction motor with wound rotor and a continuous-current machine, rigidly coupled and arranged with either two or three bearings, according to individual circumstances. Fig. 1 shows the general appearance of such converters of the three-bearing type, the rotor and armature of which are clearly shown in Fig. 2. In the latter illustration it will be noticed that the rotor and armature are not only mechanically, but also electrically coupled.

Fig. 3 shows the diagram of connections of a motor converter in its simplest form. The stator winding is shown as a star-connected 3-phase winding, but it is evident that the winding may also be mesh connected, or wound for any desired number of phases. The currents in this stator winding set up a rotating magnetic field, revolving with a speed depending upon the number of poles for which the stator is wound. This rotating field induces E.M.F.'s in the rotor windings, which are connected to corresponding points of the direct-current armature.

To make connections clearer the rotor winding in diagram Fig. 3 is shown with nine phases, although the majority of converters have been built with twelve phases. Three of the phases are connected to a suitable 3-phase starter through slip rings. The excitation of the field coils is effected in the same way as with an ordinary direct-current generator.

For the sake of simplicity it may now be assumed that the induction motor and the direct-current machine have the same number of poles (in the case shown in the diagram, two poles) and, deferring for the moment the consideration of starting, let us assume that rotor and armature are running at a speed corresponding to half the frequency of the primary circuit. In other words, the rotor is running with 50 per cent. slip, and the rotating field set up by the primary currents induces in the rotor windings a series of E.M.F.'s, which have half the

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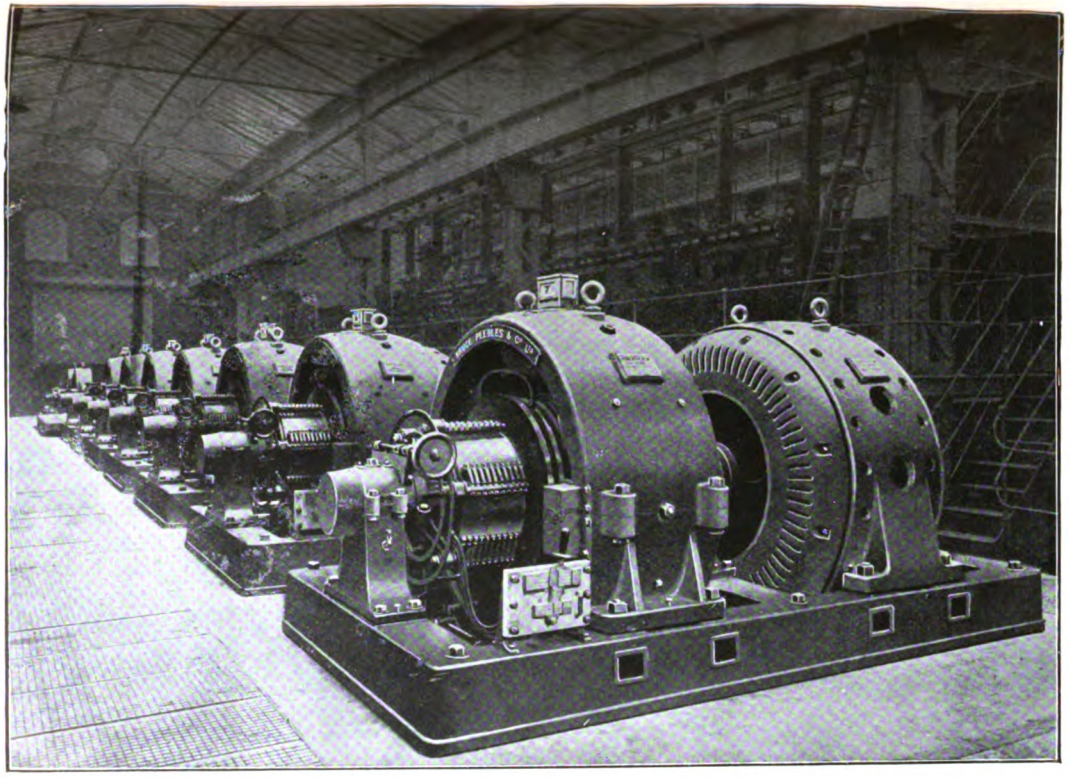

FIG. 1.—Seven Motor Converters at Shepherd's Bush Sub-station (Great Western Railway).

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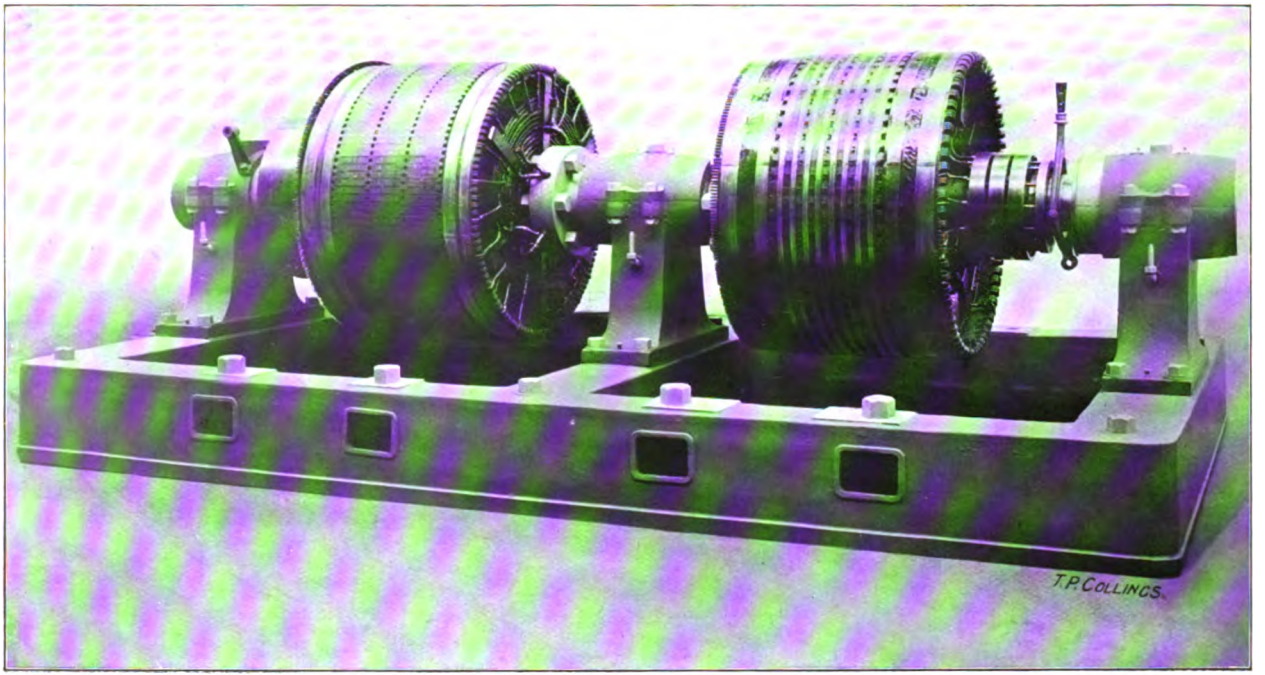

FIG. 2.—Rotor and Armature of 3-bearing Motor Converter.

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frequency of the primary circuit. Since the number of poles of the continuous-current machine is assumed to be equal to that of the induc-

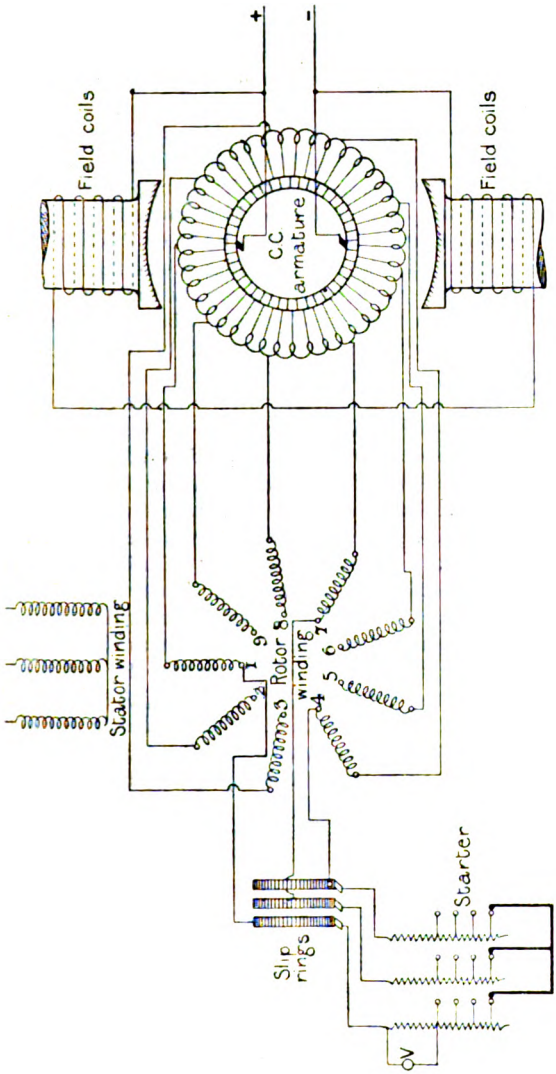

FIG. 3.—Diagram of Connections of Motor Converter.

tion motor and the armature is rotating at a speed corresponding to half the frequency of the supply circuit, it is obvious that the E.M.F.'s induced in the armature windings have also half the frequency of the

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primary circuit. For this reason it is possible to connect the rotor and armature windings together—provided they are wound with a suitable number of turns—when their E.M.F.'s are equal and in phase, and when this is done the speed remains constant and the two machines connected in tandem behave as a single synchronous machine. This will at once be realised when we study the influence of the rotor currents upon the magnetic field of the continuous-current machine. Naturally, in order that the E.M.F.'s induced in rotor and armature winding shall balance each other, the connections between them have to be made so that the rotating field set up by the rotor currents, when flowing through the armature, revolves in the opposite direction to the shaft. That is to say, this rotating field is motionless as long as the speed keeps constant, and it is the action between this field and the one set up by the magnet winding of the continuous-current machine which keeps the machine in synchronism, in exactly the same manner as in an ordinary synchronous motor. A variation in speed means a relative displacement of the two aforementioned fields, and this sets up synchronising currents just as in a synchronous motor, the only difference being that the large number of phases in the motor converter accounts for an extra strong synchronising force.

As the induction motor rotates at a speed corresponding to half the primary frequency, half the electrical energy supplied to the stator will be converted into mechanical energy and transmitted by means of the shaft to the direct-current machine, whilst the other half of the energy supplied is transferred through the rotor winding to the armature winding in the form of electrical energy. Thus the induction motor operates half as motor and half as transformer, whilst the continuous-current machine operates half as ordinary dynamo and half as rotary converter. As the rating of the induction motor depends on the speed of the rotating field and not on that of the rotor, the motor is theoretically half as large as though with the given number of revolutions it had to convert the *whole* of the energy led in into mechanical energy. The converter runs at a speed corresponding to half the primary frequency, which is more advantageous with regard to commutation; consequently it is made of smaller proportions than an ordinary continuous-current generator or converter for the same output and primary frequency.

Thus far we have only considered the case where induction motor and converter have the same number of poles. This condition, however, is not necessary. When the numbers of poles are different the converter set will not run at a speed corresponding to half the frequency of the supply circuit, but it will at once be clear that the speed must necessarily be inversely proportional to the *sum* of the number of poles of both machines. We thus find :—

$$n = \frac{60\,c}{p_a + p_c}$$

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where—

n = revolutions per minute.
c = periods per second.
p_a = number of pairs of poles of induction motor.
p_c = number of pairs of poles of continuous-current machine.

Expressing $p_a + p_c$ as p, we can say generally: The induction motor converts $\frac{p_a}{p}$ of the total supplied energy into mechanical energy, whereas the proportion $\frac{p_c}{p}$ is transferred through the rotor winding to the direct-current armature. Consequently the direct-current side deals with $\frac{p_c}{p}$ of the energy supplied as a rotary converter and with $\frac{p_a}{p}$ as an ordinary dynamo.

From this it will be seen that a further reduction of size of the induction motor is possible by taking $p_c > p_a$. Of course, p_a should not be too small, otherwise the stator winding end connections would become unduly long; moreover, it is well known that for any direct-current machine of a given output there is a definite number of poles which will secure maximum economy in construction, and it will be well to take this into consideration when determining p_a and p_c.

III. Starting.

The starting and running-up of a motor converter from the alternating-current side is a very simple matter. In starting, the alternating current—high or low tension—is supplied direct to the stator winding (see Fig. 3) and induces currents in the phase windings of the rotor. At first only three of the nine or twelve phase-windings on the rotor are utilised. These are connected, as shown, through slip rings and an external resistance to a neutral point. The external resistance is non-inductive, and is gradually cut out as the speed of the machine increases. The other ends of these three phase-windings are permanently connected to the converter armature winding. The direct-current side, of course, is disconnected from the busbars and arranged for self-excitation. It will be seen that the machine now starts up as an ordinary induction motor. Meantime, the continuous-current end is building up its field. When the machine approaches synchronous speed, the E.M.F.'s induced in rotor and armature will alternately be in opposition and conjunction, and consequently the current flowing in the starter will alternately be small and large, causing the needle of the voltmeter, which is connected across the starter resistance, to swing slowly over the scale. The periodicity of the oscillations of this needle will gradually decrease until at last it will remain at rest near the zero-point, indicating that the machine is running synchronously. The starter can now be short-circuited, and afterwards the short circuiter, shown in Fig. 2 close to

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the slip rings, pushed home. This last operation brings all phase windings of the rotor into use.

In practice it will be found necessary to insert resistance in the shunt circuit in order to bring the machine up to speed without taking excessive currents from the supply mains. This is quite obvious, if we bear in mind that the direct-current armature is really—through the rotor winding—also connected to the starter, and as long as the frequencies of the currents induced in the rotor and armature are not the same the currents flow independently of one another. For this reason a fixed proportion of the resistance of the shunt regulator is kept in circuit during the operation of synchronising. It is found advisable to adjust the starter and shunt resistance so that the machine first runs slightly over synchronous speed, to come down later automatically owing to the stronger excitation at the higher speed. The machine will then approach the synchronous speed very slowly, because the excitation—and thus the tendency of the machine to drop in speed—decreases rapidly with decreasing speed. It is possible to adjust starter

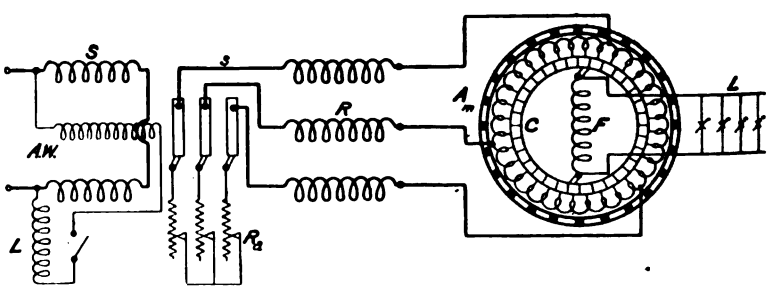

FIG. 4.—Diagram of Connections of Single-phase Motor Converter.

and shunt resistance so that no regulation whatever is required during the starting period, the attendant simply waiting for the moment to short circuit the starter and put in the short circuiter.

It will thus be seen that paralleling these converters is not at all the troublesome operation usually associated with synchronising alternating-current machines, but, on the other hand, is so simple that little skill is required for its performance, the converter coming into synchronism automatically, according to its size, within 1 to 1½ minutes after the current is switched on. Moreover the single voltmeter, connected as shown in the diagram, constitutes the whole of the synchronising apparatus required, thus conducing to the greatest simplicity in the lay-out of the sub-station. The starting current is usually about 30 per cent. of the full-load current.

In the case of a single-phase converter it is, of course, necessary to put an auxiliary winding on the stator to produce a starting torque. This is shown in Fig. 4, where the auxiliary winding is marked A W. In this case a self-induction L is put in series with the auxiliary wind-

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ing for the purpose of getting the required phase-displacement. It will be noticed that the direct-current machine is provided with an amortisseur Am. to damp the pulsations of the field produced by the rotor currents.

Naturally, the motor converter can also be started up from the direct-current side, in which case an ordinary direct-current starter and standard synchronising gear for the high-tension side is required. In order to reduce the starting current to a minimum it is well to keep the short circuiter open until the machine has made a few revolutions; otherwise part of the current will flow through the rotor windings and thus be inactive. The difference in starting current with open and closed short circuiter is usually about 25 per cent., although in special cases it may exceed this figure.

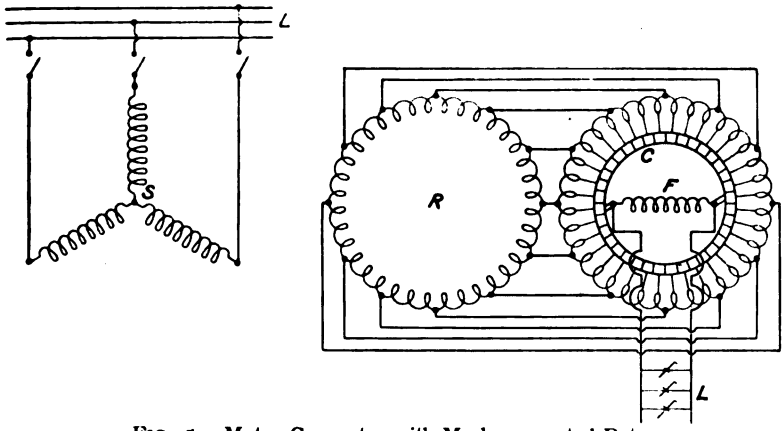

FIG. 5.—Motor Converter with Mesh-connected Rotor.

When the converter is never started up from the alternating-current side, and when there is no serious objection to the extra 25 per cent. starting current, slip rings and short circuiter can be omitted altogether, and there is no longer any necessity for winding the rotor in star. A mesh-connected rotor, as shown in Fig. 5, would do equally well. It is, however, better practice to arrange the rotor windings in star even in this case, so that later slip rings and short circuiter may easily be added, should it become desirable to start the machine from the alternating-current side. Moreover, the star-point can be connected to one slip ring to supply out-of-balance current for 3-wire systems in the manner explained later for the ordinary converter with three slip rings.

IV. THEORY.

We will now study the relation which the E.M.F.'s and currents in the various parts of a motor converter bear to one another, in order

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to determine the influence of the interconnections between rotor and armature upon the operation of the machine, and in order to get a clear insight into the methods to be adopted when designing a motor converter to fulfil certain conditions. We will first consider the induction motor.*

Say the converter takes a current I_1 per phase from the alternating-current busbars. Let the tension per phase be E_1, the number of phases m_1.

We have then the following expression—

$$I_1 = \frac{W_1}{m_1 E_1 \cos \phi_1}$$

where—

W_1 = energy in watts taken from busbars.
$\cos \phi_1$ = power factor.

The electromotive force induced in each stator phase by the rotating field is given by the formulæ—

$$E_1 = 4{\cdot}44 f_{w1} c w_1 \Phi 10^{-8} \text{ volt} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where—

f_1 = winding factor of stator winding.
c = periodicity of supply.
w_1 = number of turns in series per stator phase.
Φ = maximum flux per pole.

We have seen before that the speed of the set will be—

$$n = \frac{60 c}{p_a + p_c}$$

where—

p_a = number of pairs of poles of induction motor.
p_c = number of pairs of poles of direct-current machine.

The periodicity of the E.M.F.'s and currents in rotor and armature winding will be—

$$c_r = \frac{p_c n}{60} = \frac{p_c c}{p_a + p_c}.$$

The electromotive force E_2 induced in each phase of the rotor winding will therefore be—

$$E_2 = 4{\cdot}44 f_{w2} w_2 \frac{p_c c}{p_a + p_c} \Phi 10^{-8} \text{ volt} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where—

f_{w2} = winding factor of rotor winding.
w_2 = number of turns in series per rotor phase.

* In the following calculations the small losses in the converter are, for simplicity, neglected.

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The combination of equations (1) and (2) gives—

$$E_2 = \frac{f_{w2}\, w_2}{f_{w1}\, w_1} \cdot \frac{p_c}{p_a + p_c} E_1 = \frac{p_c}{a_e (p_a + p_c)} E_1$$

where—

$$a_e = \frac{f_{w1}\, w_1}{f_{w2}\, w_2}$$

is the ratio of transformation of the E.M.F.'s in the induction motor at *rest*.

Just as in an ordinary induction motor, transformer, or, in fact, any electromagnetic apparatus, the number of ampere-turns produced by the watt current must be the same for primary and secondary windings; consequently—

$$f_{w1}\, m_1\, w_1\, I_{1w} = f_{w2}\, m_2\, w_2\, I_{2w}$$

where—

I_{1w} = watt current per stator phase.
I_{2w} = watt current per rotor phase.
m_2 = number of rotor phases.

Hence—

$$I_{2w} = \frac{f_{w1}\, m_1\, w_1}{f_{w2}\, m_2\, w_2} I_{1w} = \frac{I_{1w}}{a_i}$$

where—

$$a_i = \frac{f_{w2}\, m_2\, w_2}{f_{w1}\, m_1\, w_1}$$

is the ratio of transformation of the currents in the induction motor.

The ampere-turns necessary for producing the magnetic flux may be supplied by the stator, by the rotor, or by both (compare the behaviour of a synchronous motor when the direct-current excitation is varied). If we assume power-factor unity at the stator terminals, the whole of the excitation is supplied by the rotor. The wattless magnetising current thus required per rotor phase may be called I_{2m}. The total rotor current I_2 per phase is then—

$$I_2 = \sqrt{I^2_{2w} + I^2_{2m}}.$$

In the case of a single-phase converter, there will still be an additional current of higher periodicity in the rotor, owing to the inverse rotating field. This field revolves with a speed corresponding to the full periodicity c in opposite direction to the rotor, and consequently the periodicity of the rotor currents induced by this field is—

$$\frac{p_a}{p_a + p_c} c + c = \frac{2 p_a + p_c}{p_a + p_c} c.$$

The value of these currents must be approximately equal to the watt current, but being of different periodicity to the watt current they cannot be added algebraically, but only geometrically; the total current in the rotor of a single-phase converter is thus—

$$I_2 = \text{approximately } \sqrt{2 I^2_{2w} + I^2_{2m}}.$$

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The electrical energy in the rotor—for polyphase and single-phase converters alike—is—

$$W_2 = m_2 E_2 I_{2w} = \frac{m_2}{a_c a_i} E_1 I_{1w} \frac{p_c}{p_a + p_c}$$

and since—

$$\frac{m_2}{a_c a_i} = m_2 \frac{f_{w2} w_2}{f_{w1} w_1} \frac{f_{w1} m_1 w_1}{f_{w2} m_2 w_2} = m_1$$

we get—

$$W_2 = m_1 E_1 I_{1w} \frac{p_c}{p_a + p_c} = \frac{p_c}{p_a + p_c} W_1.$$

The mechanical energy is thus equivalent to—

$$W_1 - \frac{p_c}{p_a + p_c} W_1 = \frac{p_a}{p_a + p_c} W_1.$$

We will now study the phenomena in the direct-current side of the converter.

Owing to the fact that rotor and armature winding are electrically coupled, there must be certain relations between the E.M.F.'s and

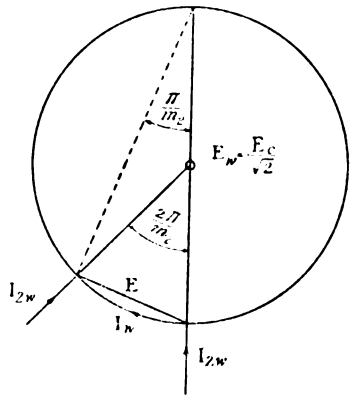

FIG. 6.

currents in their windings. These relations can be easily studied by the aid of the potential diagram of the direct-current winding, which is a circle.

Fig. 6 may represent this potential diagram. The rotor winding has m_2 phases, which are connected to m_2 equidistant points on the armature winding (referring to a bipolar scheme) their distances being $\frac{2\pi}{m_2}$ electrical degrees.

We will here neglect the effect of higher harmonics, and have thus to assume that the field curve is a sine wave. The potential curve on the commutator will then also be a sine wave, and the direct-current

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voltage E_c is equal to the amplitude of the sine wave representing the alternating voltage between two diametrically opposite points of the winding. The effective value E_w of this alternating voltage will thus be $E_w = \frac{E_c}{\sqrt{2}}$. We shall now draw our diagram for effective values, so that the diameter of our circle is $E_w = \frac{E_c}{\sqrt{2}}$. It will then be seen from the diagram that the alternating-current voltage between two points on the winding, which are $\frac{2\pi}{m_2}$ electrical degrees apart, is—

$$E = E_w \sin \frac{\pi}{m_2} = \frac{E_c}{\sqrt{2}} \sin \frac{\pi}{m_2}.$$

The electromotive force E_2 induced in each phase of the rotor winding is evidently $\frac{E_w}{2}$, the watt current per rotor phase can thus be expressed as follows :—

$$I_{2w} = \frac{W_2}{m_2 \frac{E_w}{2}},$$

where W_2 is the electrical energy transmitted to the direct-current armature through the inter-connections. The currents in the inter-connections cause currents I_w to flow through the armature windings, so that—

$$I_w = \frac{W_2}{m_2 E} = \frac{W_2}{m_2 E_w \sin \frac{\pi}{m_2}}.$$

From the two last equations follows :—

$$I_{2w} = 2 \sin \frac{\pi}{m_2} I_w,$$

or—

$$I_w = \frac{I_{2w}}{2 \sin \frac{\pi}{m_2}} \quad \ldots\ldots\ldots\ldots \quad (3)$$

I_w is thus the watt current in the armature due to the watt current in the rotor. The wattless current in the armature bears the same ratio to the watt current as the wattless current in the rotor to the watt current in same, and can thus be determined at once :—

$$I_{wl} = \frac{I_{2wl}}{2 \sin \frac{\pi}{m_2}} \quad \ldots\ldots\ldots\ldots \quad (4)$$

In addition to these currents we have still the direct current taken from the commutator.

An example will elucidate the application of these formulæ: A

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converter supplies 500 k.w. at 500 volts direct current, and takes from the mains 550 k.w. at 6,000 volts, 50 cycles. It is also used as rotary condenser to supply 35 per cent. wattless current to the busbars. The magnetising current of the converter may be taken to be 25 per cent. of the full-load current. What will be the distribution of the currents over the converter windings?

We assume $p_a = p_c$ and 12 phases in the rotor.

Watt current per stator phase—

$$I_{1w} = \frac{550{,}000}{6{,}000\sqrt{3}} = 53.$$

The wattless current is 35 per cent. of the watt current—

$$I_{1wl} = 0{\cdot}35 \times 53 = 18{\cdot}5.$$

The total current in the stator winding is thus—

$$I_1 = \sqrt{I^2_{1w} + I^2_{1wl}} = \sqrt{53^2 + 18{\cdot}5^2} = 56,$$

and—

$$\cos \phi_1 = \frac{I_{1w}}{I_1} = \frac{53}{56} = 0{\cdot}947.$$

The voltage per phase in the rotor is—

$$E_2 = \frac{E_w}{2} = \frac{E_c}{2\sqrt{2}} = \frac{500}{2\sqrt{2}} = 177.$$

Half the energy is transmitted to the rotor electrically, say 275 k.w.; the watt component of the current per rotor phase is thus—

$$I_{2w} = \frac{W_2}{m_2 E_2} = \frac{275{,}000}{12 \times 177} = 129{\cdot}5.$$

The rotor supplies 25 per cent. wattless current, required to produce the magnetic flux, and 35 per cent., corresponding to the wattless current supplied to the busbars. The total wattless current is thus $25 + 35 = 60$ per cent.

Hence—

$$I_{2wl} = 0{\cdot}6 \times 129{\cdot}5 = 77{\cdot}5.$$

The total rotor current is thus—

$$I_2 = \sqrt{I^2_{2w} + I^2_{2wl}} = \sqrt{129{\cdot}5^2 + 77{\cdot}5^2} = 151.$$

The watt current I_{2w} causes a watt current I_w in the armature winding—

$$I_w = \frac{I_{2w}}{2 \sin \frac{\pi}{m_a}} = \frac{129{\cdot}5}{2 \sin 15} = 250.$$

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The wattless current in the armature is—

$$I_{wl} = \frac{I_{2wl}}{2 \sin \frac{\pi}{m_2}} = \frac{77{\cdot}5}{2 \sin 15} = 150.$$

Moreover, we take from the commutator a current of—

$$\frac{500{,}000}{500} = 1{,}000 \text{ amperes.}$$

We have thus 1,000 amperes in the same armature conductors, which we supply with 250 amperes watt current, and from which we take 150 amperes wattless current.

We see thus that a similar question arises here as with rotary converters : we have to determine the resultant loss of these currents.

The calculation of this resultant loss is essentially the same as with rotary converters, the only difference being that only part of the direct current is overlapped by the alternating current. What interests the designer is the ratio k between the output the machine is capable of giving as converter and as ordinary direct-current machine.

It would be beyond the scope of this paper to give a detailed calculation of this ratio, but the following comparative list for rotaries and motor converters may not be without interest :—

1. Factor k for Rotary Converters.

Number of Phases.	1.	3.	4.	6.	12.
$I_{2\ l} = 0$	0·850	1·33	1·62	1·93	2·20
$I_{2wl} = 0{\cdot}3\ I_{2w}$	0·775	1·18	1·43	1·67	1·87
$I_{2wl} = 0{\cdot}5\ I_{2w}$	0·705	0·98	1·23	1·40	1·52

2. Factor k for Motor Converters with Twelve Rotor Phases.

$\frac{p_c}{p_a + p_c}$	0·3.	0·4.	0·5.	0·6.	0·67.	0·75.	
$I_{2wl} = 0$	1·30	1·44	1·58	1·74	1·86	2·00	3-phase converters
$I_{2wl} = \frac{1}{3}\ I_2$	1·29	1·42	1·54	1·66	1·74	1·82	
$I_{2wl} = 0$	1·23	1·28	1·29	1·27	1·23	1·18	single-phase converters
$I_{2wl} = \frac{1}{4}\ I_2$	1·22	1·26	1·27	1·23	1·19	1·15	

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In the list for motor converters I_{2w} and I_{2wl} have the same meaning as we have hitherto attached to them, viz.:—

I_{2w} = watt current per rotor phase.
I_{2wl} = wattless current per rotor phase.

For the rotary converter I_{2w} and I_{2wl} have a corresponding meaning—*i.e.*, are the watt-respectively wattless currents taken from the mains.

A glance at the above list is sufficient to show why modern rotaries are provided with six slip rings. Whereas for the 3-phase rotary the factor k is only 1·33, it is for the 6-phase rotary 1·93, this being a gain of not less than 45 per cent. With a 12-phase rotary the gain would be 65 per cent., but the complication of twelve slip rings renders this impracticable. With a motor converter, however, there is no objection to this large number of phases; in fact, with two bearing machines, there would be no difficulty in using more than twelve phases; the percentage gain obtained by a still further increase of the number of phases is, however, small.

The extra advantages gained by the motor converter are now at once evident. When we compare, for instance, the 6-phase rotary converter with 30 per cent. wattless current and the 12-phase motor converter under the same conditions, and with $p_c = 0{\cdot}6\,p$, we find that the factor k is the same for both; that is, all the advantages gained by the application of the motor-converter principle in the way of increased regulation, greater stability in running, etc., do not mean any additional copper losses in the armature winding, in spite of the fact that the direct-current side only works partly as a rotary.

The preceding calculations are all made with the assumption that the E.M.F.'s induced in rotor and armature have the same wave-form. This is not generally so, and in consequence currents of higher periodicity will flow through the windings, which currents will be approximately the same at no load and full load. These currents combine with the higher harmonics, resulting from the rectangular wave-form of the commutated direct current, and the resultant losses may be either increased or decreased. But since higher harmonics affect the synchronous running of machines it is always good to approach as nearly as possible the sine wave for all electromotive force curves. Since an induction motor has a greater reactance than a static transformer, the motor converter will take up smaller currents of higher frequency than an ordinary rotary converter.

V. Design.

After the explanatory theory of the preceding pages, we can be short in our indication of the method which is to be followed when designing motor converters.

Say we have to design a motor converter for a certain output and direct-current voltage, when voltage, number of phases, and periodicity of alternating-current supply are known.

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We have first to determine the number of poles on alternating-current and direct-current side. The direct-current side has to be designed as an ordinary direct-current generator for corresponding smaller output (see factor k); consequently the rules governing the choice of the number of poles there are also applicable here. With low-voltage machines one has to take care that the current per brush spindle does not exceed certain limits. We have already seen that the alternating-current side will be cheaper when the number of poles is small; a limit is set by the long stator winding end-connections and by the speed of the set. As a rule the number of poles for alternating-current and direct-current side will be equal or only differ by 2.

The design of the alternating-current side does not offer any difficulties. The air-gap need not be very small, since the magnetising current can be supplied from the rotor, and the power factor is thus not affected by the air-gap as is the case with ordinary induction motors. The only item requiring special attention is the reactance, which must be sufficient to ensure that the required voltage regulation on the direct-current side can be obtained without affecting the power factor beyond the guaranteed limits. The calculation of the influence of the reactance upon the wattless currents is the same for the motor converter as for any other synchronous machine. As an illustration of the beneficial influence the high reactance of the alternating-current side of a motor converter has upon the power factor when the direct-current volts are regulated, the following may be mentioned :—

A 500-k.w. motor converter in a well-known central station was running at 420 volts direct current with power-factor unity on the alternating-current side. The direct-current voltage was raised to 450 and the power factor went down to 0·98—that is a voltage variation of over 7 per cent. with only 2 per cent. variation in power factor.

With 390 volts direct current the power factor is also 0·98, but, of course, in this case the wattless current lags, whilst it leads when the direct-current machine is over-excited. We thus see that the power factor of this converter, when running at any direct-current voltage between 390 and 450, only varies between 0·98 and 1·00, or, in other words, notwithstanding a voltage regulation of as much as 15 per cent. being required, the power factor will under the worst conditions of running still be as high as 0·98.

The design of the direct-current end closely resembles the design of an ordinary direct-current dynamo, the only difference being that the demagnetising (or magnetising) effect of the lagging (or leading) rotor currents upon the direct-current field must be taken into consideration.

We have already found that the wattless current I_{wl} in the armature winding due to the wattless rotor current I_{2wl} is—

$$I_{wl} = \frac{I_{2wl}}{2 \sin \frac{\pi}{m_2}}.$$

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The demagnetising effect can thus be easily determined from—

$$A\,T_{DEM.} = k_o \frac{I_{wl} N}{4 a f_c},$$

where—

$A\,T_{DEM.}$ = demagnetising ampere-turns per pole.
N = total number of conductors in direct-current armature.
a = half the number of armature paths.
k_o = so-called magnetomotive force factor of a synchronous machine, and which may be taken as 0·75.
I_{wl} is positive for lagging and negative for leading currents.

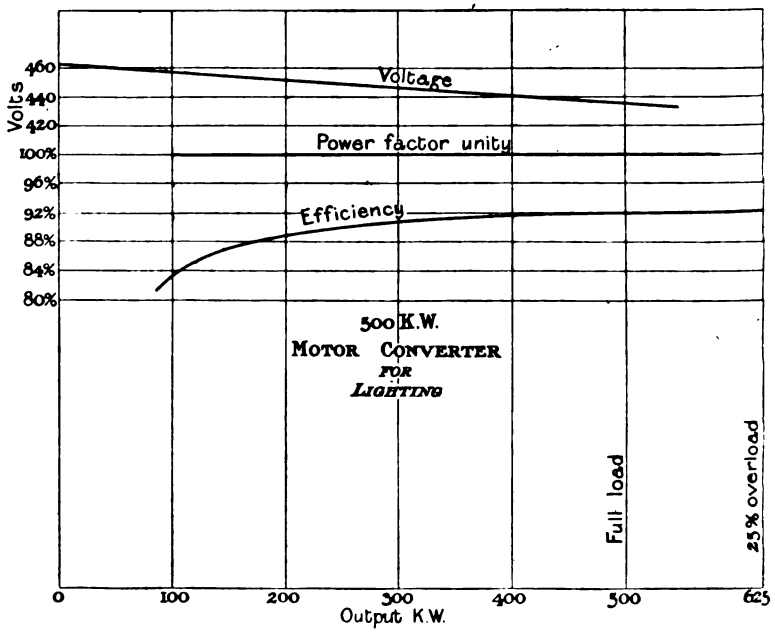

FIG. 7.—Characteristics of 500-k.w. Lighting Converter.

The introduction of commutating poles gives the designer a still freer hand, and renders the commutation sparkless with fixed brush position up to heavy overloads, independent of the direction of the current (generating or motoring on direct-current end).

VI. APPLICATION.

When motor converters are used for lighting they may be shunt or compound wound according to requirements. Shunt machines have about 5 per cent. drop from no load to full load and approximately unity power factor at all loads, as shown in Fig. 7, representing the characteristics obtained on a 500-k.w. set.

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The efficiency, especially at low loads, is remarkably high (in this case almost 86 per cent. at quarter load), and the characteristic curves of the machine shown in Fig. 8 indicate the possibility of an excellent regulation by the shunt rheostat, the power factor being well maintained within a wide range of regulation.

Sometimes a large drop in voltage from no load to full load is desirable, as, for instance, when a battery is in use floating on the busbars. Now it is possible to design a motor converter for a large inherent voltage drop, but there are also other means of accomplishing the desired effect. The most obvious one is to provide the machine

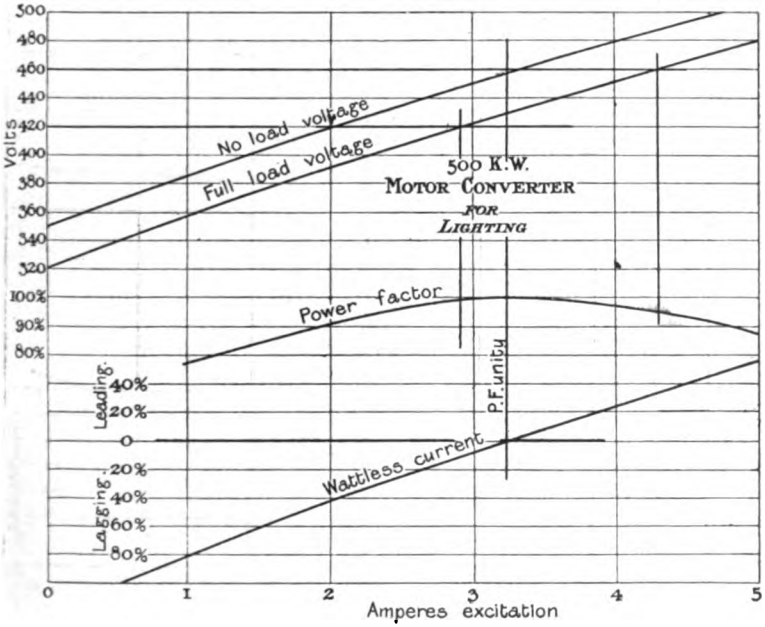

FIG. 8.—Regulation Characteristics of 500-k.w. Lighting Converter.

with a reversed compound winding, but in the case of commutating pole machines the same effect can be obtained without this complication. In this case the commutating poles are not placed midway between the main poles, but slightly forward (in the direction of rotation of the machine), thus artificially creating armature reaction, without interfering in the least with the excellent commutating qualities of this class of machine.

Motor converters for traction service will preferably automatically compound from 500 to 550 volts. The characteristics of a 500-k.w. traction converter are shown in Fig. 9; the power factor is unity at about three-quarter load, and the wattless current here changes from

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lagging to leading, which has a favourable effect on the voltage regulation of the alternators. This feature is of special value where the central station supplies both traction and lighting systems, the primary voltage remaining steady in spite of the fluctuating load on the traction converters. The machine can be fitted with commutating poles, so that they can withstand severe momentary overloads without sparking, and the freedom from liability to reversal of polarity on short circuit is of great advantage in traction installations.

Sometimes it is required that a motor converter shall be capable of supplying either a traction system at 500 to 550 volts, or a lighting system

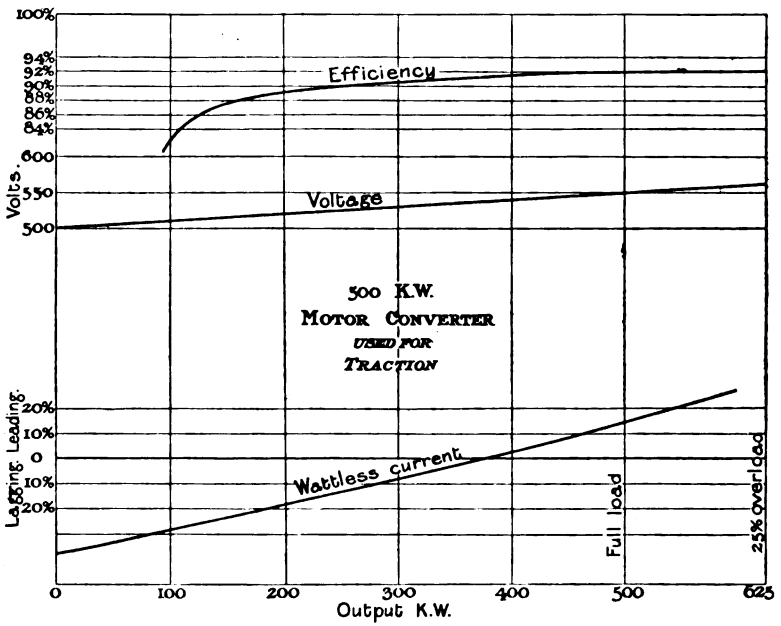

FIG. 9.—Characteristics of a 500-k.w. Traction Converter.

at, say, 420 to 460 volts. Owing to the great flexibility of the direct-current voltage, it is possible to build converters for the above extreme range of voltage, and as a matter of fact, several such machines with a voltage regulation of as much as 30 per cent. are in successful operation. In order, however, to improve the power factor in such a case it is advisable to use a synchronous booster in series with the rotor winding as shown in Fig. 10. With this arrangement unity power factor is obtained at all voltages, and the efficiency at the higher voltage is improved, the main machine acting more as converter and less as generator than would otherwise be the case. Of course, the booster need only be designed to add or subtract *half* the voltage regulation.

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Motor converters can also be used inverted. The increase of speed on inductive load is comparatively small, and does not necessitate the use of special exciters, as is the case with rotaries. The inherent regulation is excellent, the usual drop of the alternating-current voltage being 3 to 5 per cent. with unity power factor, and 12 to 15 per cent. with power factor 0·8. If voltage regulation on the alternating-current side is required it is necessary to use the synchronous booster unless the converter always runs in parallel with one or more synchronous machines, which can supply the wattless currents and maintain the frequency.

The motor converter can further be used for 3-wire supply; it is then connected as shown in Fig. 11. It will be seen that the outer

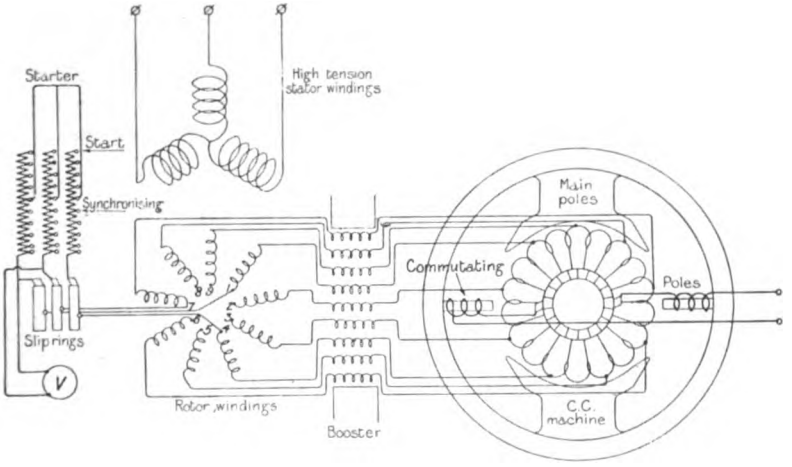

FIG. 10.—Motor Converter with Synchronous Booster.

mains are connected as usual to the positive and negative terminals, whilst the middle wire is connected to the star-point of the rotor windings, and may be earthed. When large out-of-balance currents are to be dealt with, it is necessary, in order not to overload the brushgear of the slip rings, to use a 3-pole change-over switch as indicated in the drawing (Fig. 11). When the switch is down the three slip rings are short-circuited and connected to the middle wire, so that all brushes on the three slip rings are called upon to carry the out-of-balance current. When the switch is in the other position the slip rings are no longer short-circuited, but connected to the alternating-current starter; the switch must be in this position during the starting up of the converter.

A motor converter, thus connected up, automatically balances the current, and the voltage difference between the two halves usually does not exceed 1 per cent. of the voltage between the outers, with an out-of-balance current of as much as 50 per cent. of the full-load current.

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With 20 per cent. out-of-balance current the voltage difference would be well under ½ per cent., and it is thus clear that the balance is excellent and more than sufficient for all ordinary requirements. If, however, it should be necessary to keep the voltage of the two sides of the system absolutely equal, or even raise the voltage of the heavier loaded half to compensate for the extra drop on that side in feeders and distributing cables, a booster must be put in circuit. Such a booster is series wound, and can be driven by the extended converter-shaft.

Reference has already been made to the possibility of providing a motor converter with commutating poles, and it will not be out of place to mention here how the commutating-pole circuit can be arranged with advantage in the case of converters dealing with out-of-balance currents.

With a motor-converter,* not arranged as 3-wire balancer, all commutating-pole windings are generally fixed on either the positive or negative side of the network. It is, however, obvious that this arrange-

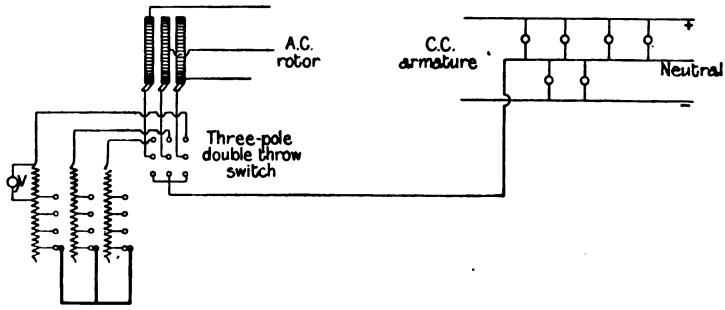

FIG. 11.—Diagram of Connections of Motor Converter arranged for 3-wire Supply.

ment cannot be satisfactory, as soon as out-of-balance currents are taken from the machine, since the excitation of the commutating poles would not then correspond to the total load on the machine.

Say, for instance, that all commutating-pole windings are connected in the negative main, and that the negative half of the network is more heavily loaded than the positive half. In this case, of course, the commutating poles will be too strongly excited, whereas the excitation will be too weak when the positive half has the heavier load. The proper excitation will be obtained when the current through the commutating-pole windings is an average between the currents in the two outers. Now, such excitation can easily be obtained by dividing up the commutating-pole circuit and by fixing the windings alternately in the positive and negative mains. When that is done, the commutation will be just as good as with machines operating on an ordinary 2-wire system.

* In fact, with all machines producing or absorbing direct current.

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It is, however, well known that, with all direct-current generators and motors, there is an advantage in fixing only half as many commutating poles as main poles. Not only does this amount to a certain saving both in material and labour, but it is an effective means of reducing the leakage flux, which plays such an important part in the design of commutating poles. This principle is, of course, also applicable to the motor converter; but it would appear, at first sight, that the use of the machine on a 3-wire system necessitates the use of the full number of commutating poles, in order to be able to divide the circuit up in the aforementioned manner. It is, however, possible in this case to use only half the number of commutating poles by fixing additional windings on the poles. These additional windings must have half as many turns as the main windings, and the current of the middle wire must pass through them.

An example will make this clear.

Say, for instance, that the main windings on the commutating poles are all connected up in the negative main, and that the currents in the + and − main are I_p and I_n respectively. The current in the middle wire will then be $I_n - I_p$, its direction depending upon which half has the larger load. For $I_n > I_p$ the current in the middle wire is positive, that is, has the same direction as the positive current,* whereas for $I_n < I_p$ the current is negative—that is, has the same direction as the negative current.†

We have already seen that the excitation of the commutating poles due to the main winding alone corresponds to I_n, whereas it should correspond to—

$$\frac{I_p + I_n}{2} = I_n - \frac{I_n - I_p}{2},$$

the difference being $\frac{I_n - I_p}{2}$—that is, the excitation is too strong when $I_n > I_p$ and too weak when $I_n < I_p$. Now, since the current in the middle wire is $I_n - I_p$, it is clear that an additional winding with half as many turns as the main winding will just compensate for the difference between the proper excitation and that produced by the main winding. Obviously, this additional winding has to be connected up in such manner that it weakens the commutating poles when $I_n > I_p$; it will then strengthen them when $I_n < I_p$ just as is required.

In conclusion, the author adds to this paper a few photographs of converters running in various sub-stations in this country.

Fig. 12 shows a motor converter of the 2-bearing type, the armature and rotor of which are built on a combined spider, so that the rotating part is very stiff, notwithstanding the long bearing span. It converts 6,500 volts alternating current of 50 cycles into direct current at 420 to 550 volts.

* We may say, the current flows *from* the machine—that is, from the slip rings when the converter generates direct current.

† We may say, the current flows *towards* the machine—that is, towards the slip rings, when the converter generates direct current.

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Fig. 13 shows armature and rotor of a 2-bearing set (300 k.w. 220 volts direct current).

Fig. 14 shows a 600-k.w. converter running at 375 revs. in the sub-station at the Manchester Exhibition of October last. The converter has 8 poles on both alternating-current and direct-current side.

Fig. 15 shows a 1,500-k.w. motor converter of the 3-bearing type from the alternating-current end. This is the largest size yet built.

Discussion.

Mr La Cour.

Mr. T. L. La Cour (*communicated*): I would call your attention to a few points with regard to design and operation. In Fig. 5 of the paper a motor converter with mesh-connected rotor is shown, which may lead to the impression that such a converter is as good as one with star-connected rotor. I do not think so myself, but as the rotor connection shown in Fig. 5 has, as far as I know, never been tried, I can only give my opinion without having been able to verify it. Both the rotor and the armature windings in Fig. 5 are mesh connected, and wound with 12 phases. Should the shape of the fields in the two machines differ materially, it is evident that idle currents will pass between the two windings. These idle currents may be considered as made up of many higher harmonics of which, in the case of a 3-phase converter, the fifth may be the most prominent. From one rotor phase to the next these fifth harmonics are displaced 5 times $30^\circ = 150^\circ$, which is a little more than the angle between the phases in an ordinary 3-phase motor. For this reason, so long as each phase of the rotor and armature windings consist of few turns and thus possess a very small self-induction, a small fifth harmonic E.M.F. will produce a fairly strong fifth harmonic current with a considerable amount of power. If, on the other hand, we replace the mesh-connected rotor winding by a star-connected one, the fifth harmonic current from the armature winding will have to pass through two rotor phases with twice as many turns as in each of the mesh-connected phases. And as these rotor phases are displaced 150° with regard to the fifth harmonic, the self-induction of these two rotor phases in series will be very large for the fifth harmonic current. In other words, the fifth harmonic E.M.F. induced in the armature winding will only produce very small currents in the rotor winding. And as this is also the case with the seventh and eleventh harmonics, the idle current passing between the armature winding and a star-connected rotor winding will be so small that it can be neglected in practical work. That is the reason why all motor converters should be provided with star-connected rotor windings, whether necessary for starting or not. For this reason, and on account of the rotating magnetic field in the induction motor which transmits the power from the stator to the rotor winding, a motor converter with star-connected rotor winding never takes up any idle current from the high-tension network.

Another remarkable feature of the motor converter which at first view impresses the engineer is the compact and strong design his class

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of machinery allows. The alternating current as well as the direct-current side resembles ordinary machines with relatively few poles, and as both machines have about the same overall dimensions the whole set resembles one compact unit and takes up a small floor space. On account of the few poles on the direct-current side the commutator is not so crowded with brushes as a rotary for the same frequency would be, with the advantage that with motor converters a flash over and burning of brushgear does not occur so often. Further, the attention which motor converters, and especially the commutator and brushgear, require, is very small. Another reason why the motor converters very seldom flash over is the large reactance and the revolving magnetic field of the induction motor. This feature leads to the problem of parallel operation, and in this lies one of the motor converter's great advantages over rotaries. On the direct-current side a good parallel operation is dependent on a fair voltage drop from no load to full load, which condition the motor converter fulfils, so that no trouble has ever been experienced on this account. On the alternating-current side a good parallel running depends on the synchronising current, as well as on the tendency to hunt and drop out of step. By designing the induction motor with a large reactance the natural frequency for hunting of a motor converter is made very low (from 75 to 150 oscillations per minute), so that no phenomena of resonance can take place between a converter designed in this way and alternators driven either by reciprocating engines which make 150 to 200 revs. per minute, or by steam turbines which work with more than 200 steam impulses per minute.

Mr. La Cour

In my opinion there are several reasons why the motor converter is specially adapted for converting alternate to direct current, and has actually found a large field in Great Britain. These reasons are not absolutely inherent to the principle by which the machine is built, but are also due to several other circumstances of which I here point out the most important :—

1. The high-tension voltage seldom exceeds 6,600 volts, which is quite safe for an induction motor.
2. This voltage furthermore varies very little with the load on account of the short transmission lines.
3. The normal frequency is 50, or lies generally between 40 and 60 cycles per second.
4. The direct-current voltage varies normally from 440 to 550 volts, which requires a generator with few poles.
5. For fulfilling the above conditions it is necessary to design induction motor with a large reactance, which in its turn gives the machine a good efficiency, especially at small loads, keeps it from hunting, and on account of the few poles on the direct-current side prevents flashing over. It is evident from the above that in spite of the principle of the motor converter having been regarded with doubt from various

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Mr. La Cour.

quarters, the practical motor converter properly designed has proved a success wherever it has been adopted, and this practical success is the best proof that the machine is absolutely rational.

Dr. Rosenberg.

Dr. E. ROSENBERG: In the first part of his paper the author never uses the expression "rotary converter" for one part of his machine, he always calls it a direct-current machine. If he had from the beginning called it a rotary converter, then he could not have maintained the many claims of advantages over the plain rotary converter. Let us consider of what a motor converter really consists. We have a rotary converter of half frequency. The rotary converter has to give half the output as a rotary converter, and the other half as a direct-current machine. It is bigger and less efficient than a rotary converter for the full output, and for half the frequency, for in a plain rotary converter the direct-current armature reaction is completely balanced by the alternating-current armature reaction. If one looks at the two tables on page 387 it would appear that the converter part of the motor converter would be practically the same as a plain rotary converter for half the frequency, but I do not think the comparison is quite correct. The author compares a 6-phase rotary converter, which has to give 30 per cent. wattless current, with the converter part of the motor converter which has to give 33 per cent. wattless current. This is not a fair comparison, because the converter part of the motor converter has to supply the wattless current which the motor part takes. The wattless current of the rotor will be more than 33 per cent., and not a single per cent. of leading wattless current goes into the supply mains; whereas in the case of the rotary converter, which supplies 30 per cent. wattless current, nearly all of it goes into the supply mains and improves the power factor. Mr. Hallo gives the magnetising current of the motor art as 25 per cent. This figure seems correct for no load, but the motor part has leakage in the primary and in the secondary, and an induction motor with 25 per cent. magnetising current takes at full load a lagging current from the line of about 40 per cent. Therefore the 33 per cent. is not even sufficient to make up for the lagging current of the motor, and a fair comparison would be with about 33 per cent. wattless rotor current in a motor converter and with unity power factor in a rotary converter. This would show that the converter part of the motor converter has to be about 20 per cent. or 25 per cent. greater than the plain rotary converter in order to give the same heating.

We have a rotary converter which is larger than the plain rotary converter, but for half frequency. What is the advantage of having half frequency for the converter part? In former times for direct-current design we did not venture to have a very high number of poles or a very high speed, but nowadays we make turbo-generators with four poles and 2,400 to 3,000 revs. per minute, which corresponds to a frequency

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of 80 to 100. A direct-current machine corresponding to a frequency of 50 is by no means out of the ordinary run. In 50-cycle converters we can use a greater number of brush arms and at the same time a higher speed, both of which are more economical and give better results for large outputs. The 400-k.w. motor converter of the Great Western station has a converter part with six poles. We have a plain rotary converter of 550 k.w. for the same voltage with eight poles—only two poles more—running at 750 revs. per minute. In fact, for large currents it gives a better machine from the direct-current side when you can apply more brush arms. It is not correct, however, to say that the number of brush arms is doubled, and no overcrowding of brushes takes place in a properly designed 50-cycle converter. Dr. Rosenberg.

Connected with the converter you have in the motor converter a motor designed for full load to run at half speed. There are the full iron losses on the stator, the full copper losses in stator and rotor, and on top of that additional iron losses in the rotor which would not be there in a plain motor running at full speed. The efficiency therefore of a motor converter is quite plainly considerably lower than in a plain rotary converter.

An interesting feature in the paper is that Mr. Hallo severely censures an additional booster to the rotary converter on page 375 "which materially affects the simplicity, cost, and efficiency"; and then on page 392 advocates the use of a booster on a motor converter which has to work on a combined lighting and traction load. The most remarkable thing in this comparison is that for exactly the range of voltage given on page 392—viz., 420 to 460 volts for lighting and 500 to 550 volts for traction—the plain rotary converter has been built and works to the greatest satisfaction without a booster, using a transformer with a small amount of reactance and providing two tappings, one for 440 volts and the other for 525 volts, regulating up and down 5 per cent. by means of the shunt regulator, and giving a very good power factor through the whole range.

With regard to the series winding in a 3-wire system mentioned on page 395 of Mr. Hallo's paper, in which only one outer main and the neutral is used, I would mention that this winding was invented by myself for compounding 3-wire machines (American patent No. 849,085).*

Mr. B. M. JENKIN: I am very glad to be able to speak on this paper, as I have had the opportunity of watching these machines from practically their start. At the beginning of the Great Western work we had a tender for them, and we had to consider them very carefully. I think I am right in saying that no machines of the kind had then been built, with the exception of a small experimental machine at Messrs. Bruce, Peebles & Co.'s works. I went up to test that machine, which consisted of an old 3-phase induction motor and an old direct-current generator, which had been roughly coupled together by their flanged coupling, and some electrical connections Mr. Jenkin.

* *Zeitschrift für Elektrotechnik*, vol. 22, p. 269, 1904.

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Mr. Jenkin. made between the armature and the rotor. We tested the machine pretty thoroughly, and I was so struck with the satisfactory way in which it worked, notwithstanding its extremely rough character, that we decided to give the machines a trial at the Great Western works, although at that time they were little known. We have been extremely pleased with the results obtained, and have never in the least regretted our choice. One of our reasons for adopting them was that they suited the conditions particularly well. We had the problem of supplying not only the power for the Hammersmith and City Railway, but also additional power for lighting Paddington station, the hotel, goods sheds, and a certain number of small motors for work about the station. It was absolutely necessary to maintain the lighting supply under all conditions if it could possibly be done, and for that reason we put in at the sub-stations some batteries of sufficient size to maintain for a short time a sufficient supply to the railway, and for a very long time a supply for lighting, should we have an interruption at the power station at Park Royal. The system of lighting in Paddington was by alternating current. We distributed 6,000 volts to the static transformers, and in order to maintain the lighting we had to keep up the alternating supply from the sub-station, so that in case of interruption from Park Royal we should in some way have to supply alternating current from the sub-stations and from the batteries. The way we decided to do that was by putting in reversible motor-generators. We had originally specified synchronous motor-generators; but when we got this tender for the Bruce Peebles motor converters we found that they did the work even better, and we adopted them on that account. In addition they had some other advantages: they occupied a very small space compared with an ordinary motor-generator. They could be started up equally well from the alternator-current and the direct-current side; they were as reversible as the synchronous machines, but required no exciters; they gave us a unity power factor, and they also gave what was of great importance—a high efficiency at full load, and also a high efficiency at low load. On comparing the efficiency curve with that of an ordinary motor-generator, one finds that the curve keeps high further back at light loads, and in consequence one gets a higher overall efficiency at the sub-station when dealing with a very widely fluctuating load, as is the case in supplying power to a railway. This condition does not arise when supplying a steady load, because in that case it is possible to vary the number of machines running, and load them up fully to the top limit, thus obtaining a good efficiency. But a railway load, which sometimes drops to nothing, and a few seconds afterwards is at about 3,000 amperes, requires machines which will work over a very wide range, and the higher the efficiency is at light loads the higher will be the efficiency of conversion at the sub-station. When we carried out the tests on these machines at the works we naturally were very careful to make them pretty complete, seeing that the plant was untried at that time. We got an efficiency of 90·5 per cent. at full load. Those, I should

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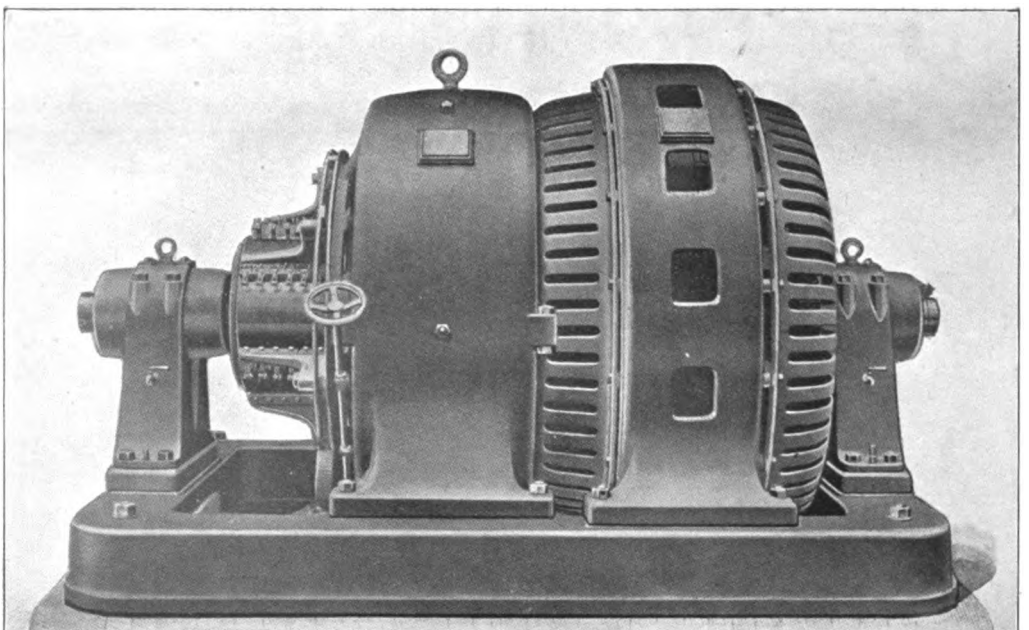

FIG. 12.—500-k.w. 2-bearing Motor Converter (Manchester Corporation Electricity Works).

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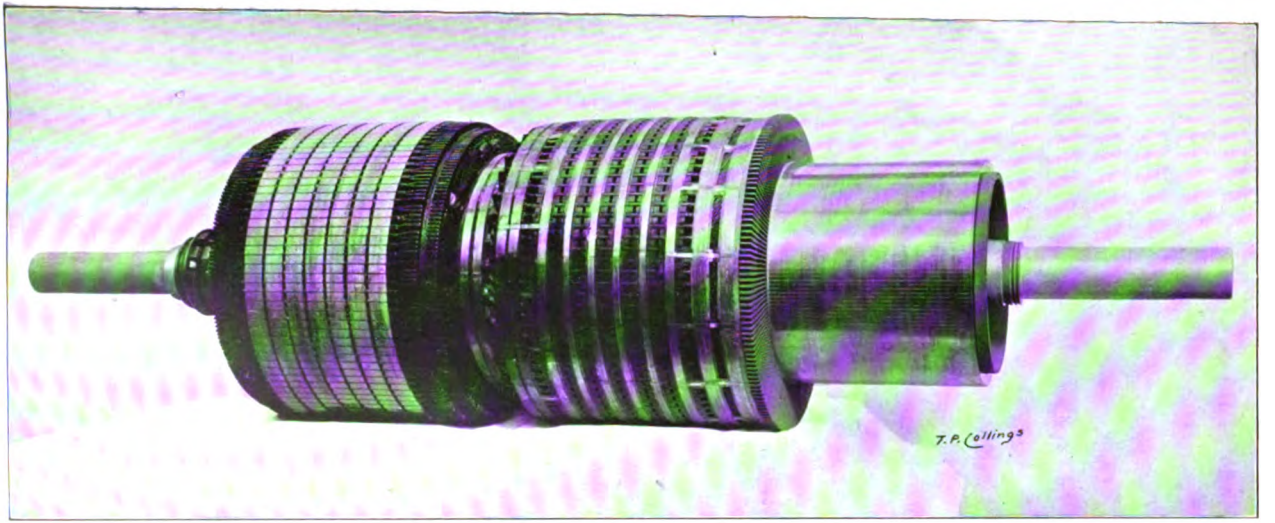

FIG. 13.—Rotor and Armature of 2-bearing Motor Converter (Great Eastern Railway).

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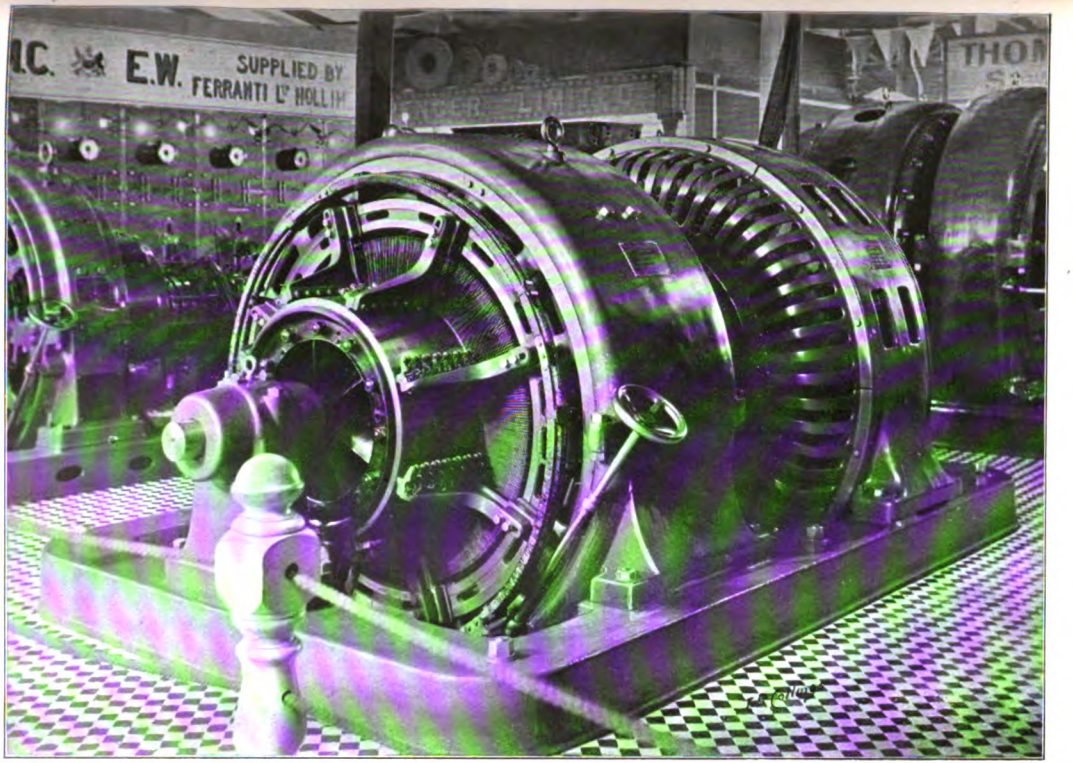

FIG. 14.—600-k.w. Motor Converter at Manchester Exhibition.

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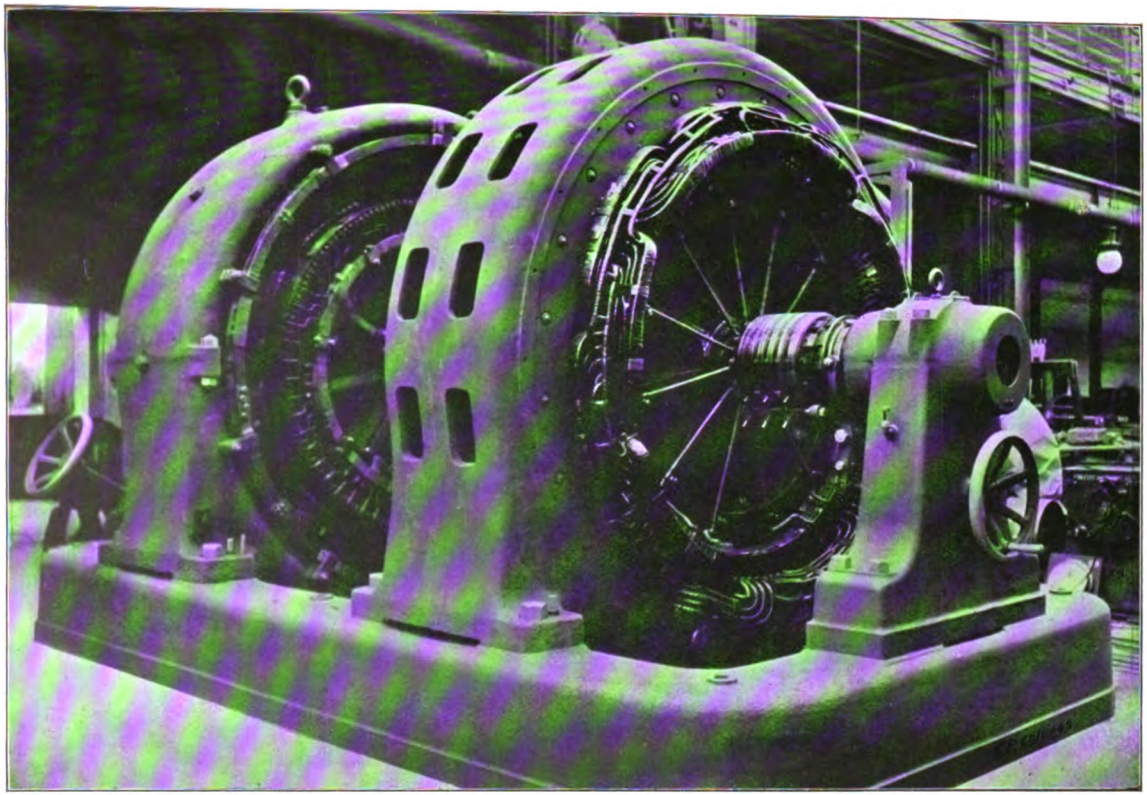

FIG. 15.—1,500-k.w. Motor Converter from Alternating-current End (Manchester Corporation Electricity Works).

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Mr. Jenkin

say, were some of the first machines built, and had three bearings, and connections through the shaft. No doubt with later types and with two bearings, the 92 per cent. given by Mr. Hallo in his paper is a figure that could be obtained. As to reversibility, I remember on one occasion we were running two machines in Hopkinson, coupled on the direct-current side and also on the alternating-current side, so that there was one of the machines working under normal conditions converting alternating to direct-current, and the other working in the reverse direction. With one of the direct-current machines loaded up to 30 per cent. overload, without touching anything but the regulators, we reversed the power, so that the direct-current machine was running as a motor with a 77 per cent. kilowatt overload. This really meant 100 per cent. overload in amperes through the armature of the motoring machine, and it did this with practically no sparking. I think that was a pretty severe test, and showed the reversibility, and the reliability of the machine for that purpose. Mr. Hallo has pointed out that the machine is normally running at about half-synchronism, and it is held at the right speed by the direct-current field, so that if you break the direct-current field the machine will run up to true synchronism of the induction motor, which is approximately double speed. I wanted when testing the Great Western Railway plant to see if things were safe should this happen. We broke the field, and the machine ran away, but everything went all right. It sounded a little alarming, but nothing happened. There are one or two peculiarities which I think may be emphasised in connection with these machines, as they must be borne in mind in considering the arrangements of switchgear and the use of the machine. In starting from the alternating-current side one must be careful that the direct-current machine builds up as it gains speed. Should it not do so, of course the machine will run up above the right speed, and must be shut down and re-started. After the machine has its residual magnetism established, it will be practically certain to build up, but care must be taken that the direct-current voltage comes up as the alternating-current machine is started. Again, the fact that the machine is, so to speak, a transformer, has to be carefully borne in mind in settling the voltages. With fixed loads on the machines the direct-current voltage will vary as the alternating-current voltage varies. The direct-current voltage can be regulated by the rheostat to any required point; but if no regulation is made and the alternating-current voltage varies, the direct-current voltage alters too. In starting from the direct-current side the machine is run up to speed with the direct-current machine acting exactly as an ordinary direct-current motor. The speed is regulated by the rheostat to the right point for synchronising and switching in, but in order to regulate the alternating-current voltage while synchronising, the simplest way, and the one we adopt, is to regulate the direct-current voltage. As the direct-current voltage is raised the alternating-current voltage comes up, and can be stopped at the right point. We are running off a battery, and we simply increase

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Mr. Jenkin. the voltage on the booster between the battery and the busbar. That is a much better method than having any additional booster on the machine itself. We must have the battery booster, and therefore we can regulate our voltage in that way. When we had erected the machines on the site we made fairly complete tests to ascertain how they behaved under actual working conditions. One of the tests we made was to run for 48 hours, taking the measurements at the power station and sub stations throughout. For the first 24 hours we worked with the batteries at the sub-stations, and for the second 24 hours we worked without the batteries, as we wished to see what effect the batteries had on the efficiency. You will remember that the primary reason for putting in batteries at the sub-stations was to insure continuity of supply for the lighting. That was our primary object. But there was an additional object we hoped to gain, namely, to steady the load on the motor-generators, to reduce the extremely peaky nature of the load from the railway, and in that way to be able to run less plant at the sub-stations and less plant at the power house, and so improve the efficiency of working. Taking the results at one of the sub-stations only, on the first day, when we had the battery, we run two motor converters. On the second day, without the battery we had to run three to take the load. The fluctuation in load was, with the batteries, a minimum on each machine down to 38 per cent., with a maximum of 116 per cent.; in other words, they were 16 per cent. overloaded. On the second day the load went down to nothing, of course, and also up to 32 per cent. overload. The fluctuation on the high-tension volts produced by this big variation on our motor converters on the first day was 2·7 per cent. I mention this because on that depends the steadiness of the lighting, if it is supplied from the same busbars from which the traction load is taken. The fluctuation on the high-tension volts with the batteries was 2·7 per cent. up and 2·7 per cent. down. On the second day it was 6·8 per cent. The mean load on the generators on the first day was 75 per cent. of their full load. By that it will be seen that they were pretty well loaded as we had the battery. On the second day it was 43 per cent. The motor-converter efficiency and direct-current output to high-tension input of the machines was 89 per cent. on the first day and 82 per cent. on the second day. The greater variation of our load on the second day brought the efficiency down, but still 82 per cent. is very high for a load which constantly dropped to nothing. The battery losses, of course, on the first day reduced the sub-station efficiency somewhat, and the overall efficiency of the sub-station on the first day with the battery was 78 per cent., and on the second day without the battery was 82 per cent. Now on those tests we were not working the lighting load off the same busbars: we had separated that altogether, so that it was entirely traction load, and a traction load of the very worst character. We have usually only three trains being supplied from our sub-stations, five at the most, and the kind of load can well be imagined. I would like to point out that this figure of 82 per cent.,

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which is obtained with an extremely difficult load to deal with, and without the batteries, compares directly with the sub-station efficiency that we heard of the other day in regard to the London County Council, where with ordinary motor-generators they obtained 75 per cent. Mr. Jenkin.

Mr. ROGER T. SMITH: I have only a few words to add to what Mr. Jenkin has already said with regard to the sub-station equipment which Messrs. Kennedy and Jenkin carried out for the Great Western Railway. He has nearly exhausted all that can be said about one installation. Mr. Hallo has referred in his paper to the quality of the motor converter in giving leading currents above a certain value of the load. This we have found to be a most important property of the motor converter, and as a matter of fact, at the loads at which the machinery is usually working in the Great Western sub-stations the wattless current is always leading. On very high peaks the power factor falls as low as 92 per cent., but when running with a battery under ordinary conditions it goes up to 98 per cent. These leading currents help the lagging currents of the generators at the generating stations, with the result that their regulation is improved, and the successful solution of the very difficult problem of keeping a steady voltage at the generating station busbars for lighting is thus considerably helped by the leading currents in the motor converters. I might also say that another very excellent feature is their overload capacity. During the running of the Exhibition traffic last year it was quite common to have the motor converters overloaded 60 per cent., by which I mean that all the motor converters in a sub-station taken together are overloaded 60 per cent. These overloads, however, last for very few seconds at a time. The reversible motor booster of the Highfield type does not reverse quickly enough to take up the overload as it comes on, so that this overload at first has to be taken up by the motor converters. As soon as the booster is properly reversed and has come up on to its load it overtakes the overload of the motor converters, which drop back to normal working while the battery through the booster takes the continued overload. Without this high overload capacity of the motor converters they would not be nearly so successful as they are in working with batteries. When the paper was announced I thought it might be of interest to make another test, supplementary to the test referred to by Mr. Jenkin just now. During eleven days, including Easter week, which was chosen as containing the very worst possible conditions that one could have, a test of the machines was made at the sub-station at Shepherd's Bush which is illustrated in the paper, and the results are given below. Mr. Smith.

The average daily machine load factor is 51 per cent., and the average daily efficiency of the machines is 83½ per cent. This, it will be noticed, is considerably lower than the 89 per cent. for another sub-station mentioned by Mr. Jenkin. The reason for this is, I think worth noting. At the sub-station which had a machine efficiency of 89 per cent., the battery was of 1,000-k.w. capacity; at the sub-station

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Mr. Smith. where the machine efficiency was 83½ per cent., the battery was of 500-k.w. capacity. The commercial efficiency of the whole sub-station, as between the alternating-current input and the direct-current output to the track, was, however, almost exactly the same—78 per cent. in the case of the sub-station with the big battery, and 79 per cent. in the case of that with the small battery. In this particular instance therefore it is clear that, looked at only from the point of view of commercial efficiency, so big a battery (36 per cent. of the output goes through it) does not pay. The higher efficiency of the machines is all lost by conversion in the battery. As Mr. Jenkin explained, the size of the larger battery was chosen for quite other reasons than sub-station effi-

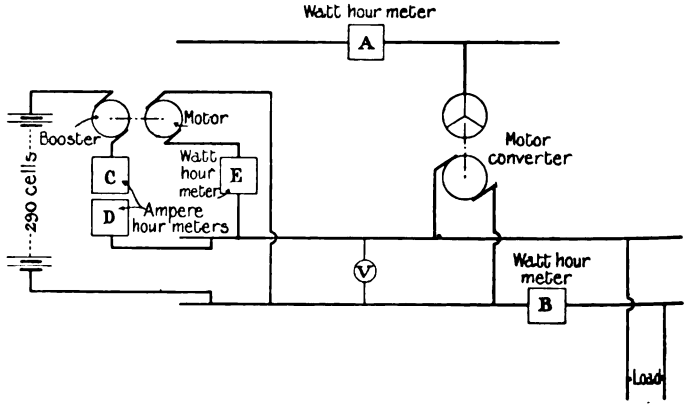

FIG. A.—Shepherd's Bush Sub-station.

(Diagram showing Positions of Meters used in obtaining Machine Efficiency.)

A = High-tension alternating-current input to sub-station.
B = Direct-current output from sub-station.
C = Charge ampere-hours × average busbar volts.
D = Discharge ampere-hours × average busbar volts.
E = Booster motor kilowatt-hour.
V = Busbar volts.

ciency—namely, the running of the Paddington lighting for 10 hours in case of a bad breakdown. I should only like to say, in conclusion, that if the Great Western job had to be done all over again, not only those who have to pay for the machinery, but those who have to work it, would all wish to have motor converters in the sub-stations.

The diagram of connections shows the meters used, the lettering of the meters corresponding to the lettering above the columns of results. From this it will be seen that the high-tension alternating input is metered, as also the low-tension direct-current output to the track. About 12 per cent. of the total output goes through the battery, part being absorbed by the motor of the booster, the energy being metered, and the other part being the net difference between the charge and

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SHEPHERD'S BUSH SUB-STATION.

Machine Efficiency.

April, 1909	Kilowatt-Hour. A.* High-tension Input.	B* Track Output.	C.* Battery Charge.	D.* Battery Discharge.	E.* Booster Motor.	B + C + E − D. Machine Output.	Machine Hours.	Machine Load Factor.	Average Power Factor.	Machine Efficiency.	Sub-station Efficiency.	Remarks.
								Per Cent.		Per Cent.	Per Cent.	
Thursday, 8	18,900	14,698	2,103	1,947	706	15,560	66·30	58·6	92-98 leading.	82·3	77·6	
Friday, 9	12,900	10,261	1,486	1,441	503	10,809	58·60	46·5		83·7	79·5	Good Friday.
Saturday, 10	15,780	12,332	1,801	1,670	595	13,148	63·90	51·4		83·3	78·2	
Sunday, 11	10,410	7,834	1,542	1,602	394	8,168	56·40	36·2		78·5	75·2	
Monday, 12	14,590	11,444	1,737	1,540	510	12,151	63·70	47·7		83·2	78·5	Easter Monday.
Tuesday, 13	17,720	14,198	1,782	1,750	501	14,731	65·60	56·1		83·1	80·0	
Wednesday, 14	16,040	13,317	1,564	1,660	482	13,503	65·20	51·7		84·1	81·8	
Thursday, 15	17,220	13,311	1,958	1,538	475	14,206	64·60	54·9		82·5	77·4	
Friday, 16	17,040	14,464	1,780	1,623	460	14,981	64·75	57·8		83·4	80·6	
Saturday, 17	19,080	15,218	1,940	1,620	696	16,234	64·75	62·6		85·0	79·9	
Sunday, 18	10,180	8,017	1,269	1,588	493	8,191	56·55	36·2		80·4	78·7	
Total ...	170,760	134,895	19,052	17,979	5,815	141,783	690·35	560·0		919·5	867·4	
Average ...	15,524	12,263	1,732	1,634	529	12,889	62·70	50·9		83·5	78·8	

* See diagram.

Mr. Smith.

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Mr. Smith. discharge of the batteries through the booster. The battery meters are, of course, ampere-hour meters, and their readings are multiplied by the busbar voltage. This voltage remains so constant that the error due to this is certainly not greater than the error in the wattmeters themselves. Since the total energy going to the track is metered, if to this quantity are added the metered input to the motor of the booster and the metered energy of the charge to the battery, and the metered energy of the battery discharge be then substracted, the result will be the total output of the motor converters. During Easter Monday overloads of the whole of the motor converters, amounting to 50 per cent., were repeatedly noted.

Mr. Seabrook. Mr. A. H. SEABROOK: I cannot agree at all with the first two pages of the author's paper. The first point I have to quarrel with is the question of the reliability of rotary converters on 50-period systems. We are now running about twelve sub-stations in one district, three being rotary sub-stations, and one of the latter runs day and night continuously. One man does the whole of the attendance at those sub-stations. We have various makes. Some of our rotary converters were made by people who have only made one or two machines; others were made by people who have had more experience; and there is not the slightest trouble—as I think is shown by the attendance required—in running rotary converters on a 50-period system. In the third paragraph of the first page the author refers to starting up. There is no difficulty in starting up rotaries as induction motors with tappings on the transformers. The ordinary factory hands attend to them. The machines start in the morning, and they are attended to by the people who look after the factory. With regard to polarity something may be said, but a double-pole switch and voltmeter arrangement is a particularly simple and inexpensive way of getting over that slight trouble. On page 375 the reversibility of the rotary converter is rather questioned. I know a rotary converter that is running the reverse way at Barking, installed a year ago by Mr. Howard, the engineer there. It runs day and night on an inductive load, is driven from the direct-current side, and gives an alternating-current output. There has not been the least trouble in running the machine. They have not even a spare rotary, but only a spare armature, which is put in when the commutator requires turning up. Lower down on the page the author refers to efficiency; in connection with day and night continuous running with, say, a 90 per cent. load factor, efficiency is a very important point. From my experience of quotations, specifications, guarantees, etc., it would not pay to run motor-generators or motor converters with a day and night load, even if they were supplied free of charge. A difference in efficiency of 1 per cent. is a very much more important item than any one would imagine who had not worked it out for himself. The last point on which I differ with the author is as regards the floor space. It is quite wrong to say that motor converters take up less floor space than rotary converters and transformers. The transformers can be put out of doors, in a cellar, in a basement, or

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on a roof. There is not the slightest necessity to put them on the same floor as rotary converters if it is a question of space. I am rather inclined to throw out a challenge to the author to show why a motor converter or motor-generator should be used as against a rotary converter for any purpose on the question of cost? The capital cost is considerably higher, and the efficiency of any motor converter or motor-generator plant is lower than that of a rotary plant. Greater attention is required for any motor converter or generator than for a rotary, and on account of the high-tension current being necessarily put on the stator winding there is greater liability to break down. As a user of both rotary converters and motor-generators I would say that by putting in rotary converters capital cost is distinctly saved and efficiency gained. Mr. Seabrook.

Mr. F. BAILEY: It has been a pleasure to hear of the successful application of motor converters, especially from the speakers who mentioned the Great Western Railway. They pointed out the necessity of obtaining perfect and reliable lighting. I might mention the extraordinary success of the original plant at Paddington, which I put down between 1883 and 1885, and which ran for twenty-two years with absolute reliability. During that time the light never failed once, and it is gratifying to learn that the new works at Park Royal and the motor converters have maintained that average. I have been using motor-generators for some time, and some years ago when designing the Willesden works of the Metropolitan Company I had the opportunity of testing some of the early forms of rotaries, and I found we could hardly depend upon them. The frequency was then 60 or 66. Sometimes they would reverse, and at other times they would hunt. The result of that preliminary test was to drive us to motor-generators. Since that time I have been using motor-generators for the Bankside works of the City of London Company, and last year we put into those motor-generators about 4,719,000 units, and we got out of them 3,675,000 units, an overall efficiency of 77 per cent. Therefore on the question of efficiency I think the author was quite justified in drawing attention to the remarkable results which may be obtained by a machine giving not only a higher intrinsic value in efficiency, but a better general overall efficiency. We also find, in dealing with motor-generators, that it is not always easy to handle them with sufficient rapidity, and I think the author was very wise in calling attention to the short time required to start the motor converter. Mr Bailey.

Mr. J. S. PECK: It has always seemed to me that the development of the motor converter was based upon the fallacy that the high-frequency rotary converter could not be made to operate successfully, but after what we have heard as to the number of these latter machines now running any fair-minded man must admit that the high-frequency rotary can be made a satisfactory piece of apparatus. If that is admitted, then I think it follows that the higher efficiency, the lower cost of manufacture, and the greater reliability of the rotary, which has no high voltage on the stator windings, will insure its gradually replacing all other types of converting apparatus. Mr. Peck.

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Mr. Peck. One would think from what the author says that the rotary converter has made but little progress in this country since 1904. As a matter of fact, the company with which I am associated has installed over 160,000 k.w. in rotary converters since 1904, and over a quarter of this has been for high-frequency circuits.

It is stated in the paper that in 1902 the motor converter was patented by Messrs. Bragstad & La Cour, but the author neglects to say that the fundamental patent in the motor converter is due to M. Maurice Le Blanc, and was taken out in 1899. I believe that all companies manufacturing motor converters to-day recognise his patent in the form of royalties. With regard to the question of starting, I think, from what both Mr. Jenkin and Mr. Seabrook have said, it can be seen that there are two sides to that question, and that the starting up of a motor converter is not quite so simple as it would appear from the paper. In the first place, there are two rheostats, one in the rotor circuit and the other in the field circuit, which have to be worked more or less simultaneously, and as Mr. Jenkin says, care must be taken to see that the field builds up as the machine comes up in speed, otherwise the machine may run up to double speed, and with not quite such satisfactory results as Mr. Jenkin obtained. When the machine has reached approximately the correct speed a few slight adjustments are made, and it may then be synchronised, but synchronising is necessary, and whether it be done by a voltmeter, as with a motor converter, or by means of a lamp or synchroscope as with a rotary, makes little difference.

With regard to the voltage regulation which it is possible to obtain on a rotary converter by field adjustment only—*i.e.*, without a booster—it is possible, by placing reactance in the circuit, to do everything on a rotary that can be done on a motor converter. The reactance can be obtained in the transformer without sacrificing efficiency, or may be placed outside in the form of choke coils. With the same amount of reactance in the rotary circuit as in the motor converter, the regulation curve of the rotary will be the same as shown in the paper for the motor converter.

Regarding floor space, it is admitted that a rotary converter with its transformer may take up slightly more floor space than a motor converter, though in certain cases the starting resistance supplied with a motor converter is practically as large as the transformer for the rotary. If, however, a station is built specially for rotary converters, it is the usual practice to put the transformers in a gallery or in a basement, as they require no attention. A good illustration of the possibility of getting a large capacity of rotary converters in a small space is shown in the Charing Cross sub-station of the Underground Electric Railways. I do not believe that an equal capacity in motor converters could possibly be squeezed into this sub-station.

With regard to the table of copper losses on page 387, Mr. Hallo, in order to make the copper loss of the motor converter equal to the copper loss of the rotary converter, has chosen a combination of poles

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in his two machines, which he admits is not the usual one. If he takes the usual combination of poles, then the copper loss of the rotary is considerably less than that of the motor converter when working under similar conditions. Mr. Peck.

The efficiency curve on page 390 is certainly a remarkable one, and it would be interesting to know the separate losses which enter into the curve. The exact shape of the curve appears to be impossible of realisation, as any one can determine if he tries to find losses which will give a curve passing through all the points. The efficiency at full load is certainly remarkably high, and it would be interesting to know whether the machine was built with special Stalloy steel.

With a rotary converter it is always possible to carry a spare transformer, or to carry a few spare coils. In the event of a breakdown in the high-tension winding, the spare transformer may be substituted, or the transformer may be repaired in the course of a few days, whereas a breakdown in the high-tension stator winding of a motor converter usually requires several weeks to repair. The highest voltage for which it is safe to wind an ordinary size motor converter is about 6,000.

For higher voltages it is, in general, necessary to use transformers. This, of course, puts the motor converter at a great disadvantage as compared to the rotary.

It has been stated that the switchgear for a rotary is more complicated than that for a motor converter. This is not true if the transformer is connected directly to the rotary, which is quite common practice. The fact that switches may be placed, if desired, between the transformer and rotary is an advantage for the rotary, and not a disadvantage, as advocates of the motor converter would have us believe.

Communicated: I think it will be admitted by any one experienced in the testing of electrical apparatus that the separate loss method of obtaining efficiency curves gives far more accurate and consistent results than does the input and output method. There are certain very good reasons for this. By the input and output method, the loss is a small difference between two large quantities, and a 1 per cent. error in either gives practically a 1 per cent. error in the efficiency. In commercial testing, readings to within 1 per cent. are very good, so that by the input and output method errors of 2 per cent. in efficiency are quite usual. By the separate loss method, however, an error of 1 per cent. in reading means a very small fraction of 1 per cent. error in the efficiency. The chance for error in this method is in omitting some of the separate losses, also on account of the fact that the losses under full-load conditions may be different from these taken separately; but in general, the chances of error are much less in the separate loss method than in the input and output method. Another difficulty in obtaining accurate results by the input and output method is the fact that a large number of instruments have to be read simultaneously, and any one who has tried commercial efficiency tests by this method will know how nearly impossible it is to obtain a degree of accuracy in readings which will give results of any value.

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Mr. Peck

In comparing the efficiency of the motor converters with the motor-generators at Manchester, Mr. Hallo stated that Mr. Pearce would not have a rotary converter on his circuits. It may interest members of the Institution to know that Mr. Pearce has recently installed a rotary converter of 700-k.w. capacity. In his argument regarding floor space, Mr. Hallo overlooked the fact that the transformer has no moving parts, and requires no attention, so that it may be placed in positions which are quite unsuitable for such apparatus as motor converters, rotaries, or motor-generators. In America, the practice seems to be coming into favour of placing even high-voltage transformers out of doors, while the placing of transformers in basements or in galleries is well-established practice everywhere.

In conclusion, I would say that the advocates of the rotary converter have never claimed that the motor-converter or the motor-generator were not satisfactory machines. What they do believe is, that for frequencies not exceeding 60 periods, the rotary converter will prove to be much more efficient, especially at low loads, that it is considerably cheaper to manufacture, and that it has a number of minor points of superiority, which in themselves are frequently of sufficient importance to turn the scale in its favour, while for low-frequency circuits the rotary converter is the only machine to be considered, except for certain very abnormal conditions, where the motor-generator may be preferred. In order to show the efficiency obtained on the rotary converter, I give below the overall efficiency of a 550-k.w. 550-volt 750 revs. per minute rotary, with its 6,600-volt 3-phase transformer. This is a commercial machine, and no special features are embodied in its construction for obtaining unusually high efficiencies :—

Combined Efficiency of 550-k.w., 550-volt Rotary Converter with its Transformer.

25 per cent. overload	...	...	...	...	95·05	per cent.
Full load	...	...	...	...	94·85	„
¾ „	...	...	...	...	94·06	„
½ „	...	...	...	...	92·30	„
¼ „	...	...	...	...	87·25	„

Professor Arnold.

Professor E. ARNOLD (*communicated*) : The advantages of the motor converters are appreciated on the Continent, and several of the leading manufacturing firms have already built a number of converters of this type with great success, and others are in course of construction. A remarkable plant has recently been installed by Messrs. Brown-Boveri & Co. for the electrochemical works at Ammendorf, in Saxony. The power is generated in two 3-phase 50-cycle turbo-alternators of 1,000 k.w. each, 2,000 revs. per minute, 500 volts. The 3-phase current is converted into direct current by means of two motor converters of 900 k.w. each, 160–175 volts, 5,600–5,150 amperes, 214 revs. per minute,

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the induction motor having 12 poles and the direct-current machine 16.* The motor converters were chosen for their high efficiency compared with motor-generators. With the heavy conditions of a continuous 24 hours' full load running a difference of efficiency from 2 to 3 per cent. means a reduction of cost of at least 6,000 to 9,000 marks (£300–450) a year. Professor Arnold.

Among the good qualities of motor converters stated by the author, the relative low first cost and the high efficiency seem to be the most important, and special attention should be drawn to the fact that the efficiency has still high values at half-load and even at quarter-load, as may be seen from Figs. 7 and 9 of the paper. In this respect the motor converter is greatly superior to the motor-generator.

Referring to the 3-wire supply, the author has stated that motor converters can be built with half the number of commutating poles by using, in addition to the main excitation winding of these poles, an extra winding with half the number of turns and supplied with the middle-wire current. It appears to me that this extra winding may be dispensed with if the main excitation winding is divided into two equal portions, and the one half supplied with the positive, the other with the negative main-wire current, thus giving an excitation corresponding to $\frac{J_p}{2} + \frac{J_n}{2}$ as required.

Mr. K. FAYE-HANSEN (*communicated*): In his paper Mr. Hallo claims advantages for the motor converter over the rotary converter due to the higher reactance of the induction motor compared with the transformer. This claim rests, however, upon a mistake, as the transformer, besides the advantage of high efficiency and increased safety for high voltages, also has the advantage compared with the induction motor that *any* reactance required can be obtained between very wide limits. I have thus in the last year designed a number of transformers having different reactances between the limits of 0·5 and 30 per cent., and experience proves that a transformer with the reactance of 20 to 30 per cent., as now usually employed by the Westinghouse Company for rotary converters, is cheaper and has as good an efficiency as transformers with ½ to 1½ per cent. reactance, such as are often required for power and lighting. In a special case I have even designed transformers having a reactance of over 50 per cent. This was a 3-phase auto-transformer to be used in conjunction with a rotary for 425 volts direct current running off a 400-volt 3-phase line. As an auto-transformer it had a reactance of 20 per cent., which corresponds to a reactance in an ordinary transformer of about 55 per cent. The reactance in a transformer can be predetermined within the same limits of accuracy as the short-circuit current for a 3-phase motor. The transformer has further the advantage that in many cases the reactance can be altered easily and cheaply after the transformer has been built up. This has proved useful in the case of a few cabled Mr. Faye-Hansen.

* An illustration of these machines is given in E. Arnold, *Die Wechselstromtechnik*, Band v., Teil I., *Die Induktionsmaschinen*, p. 508.

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Mr. Faye-Hansen.

orders from abroad, where the confirmation of the order has shown that the conditions were such that a different reactance to that first intended was desirable. The only difficulty with high reactance is for 3-phase transformers with unsymmetrical cores, as it is difficult to provide more than 30 per cent. reactance in such cases and obtain the same reactance on all three phases, owing to the magnetic interlinking of the leakage lines. For any other type of transformer, however, there is no difficulty in obtaining reactance considerably higher than that which can be obtained in a 3-phase induction motor.

I have dealt with this question at considerable length because the prevailing opinion seems to be that transformers have inherently a low reactance, while the fact is that *special* transformer windings have to be adopted for this purpose and are becoming standard, as in most cases a low reactance is required. Any one who has had much experience in the designing of transformers, however, will know that the difficulty as a rule is not to get a high reactance in a transformer, but to get a low one. The ease with which any desired reactance can be obtained in a transformer is one which makes the rotary converter suitable for many services for which the motor converter cannot be used with advantage. For instance, when the rotary is to be used as a condenser for obtaining power-factor unity on the network it can be supplied with a transformer having a very low reactance, so that it can supply the magnetising current required under different conditions of the network and still maintain the same direct-current voltage, which is not possible with the motor converter if a booster is not used. If the rotary has to run from direct current to alternating current the transformer will be designed with low reactance, which, compared with the high reactance of the induction motor, makes the regulations of the rotary plant very much better than that of the motor converter, the voltage drop being in the neighbourhood of one-third or less of that of a motor converter. If no special reactance (low or high) is required for other purposes, the reactance of the transformer can easily be made of the size giving the largest stability against hunting, etc., while in the case of the motor converter the reactance will have to be that suitable for the design of the induction motor. A further advantage of the transformer over the induction motor is that it can easily be provided with tappings on the high-tension side so that the rotary may be used for the purpose of lighting and traction without booster, and still be running at the best possible power factor in both cases. If the alternating-current voltage is specially low an auto-transformer can in many cases be used, thereby still more increasing the superiority of the rotary plant regarding price and efficiency. In case of really high-tension voltages (10,000 or higher according to size) it will be necessary to use a transformer also for the motor converter, and in this case, of course, the difference between the motor converter and the rotary plant will be very large. There is only one thing the induction motor can do and the transformer not, and that is to alter the periodicity of the supply for the rotary, while in *all* other respects

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the transformer can do the same work as the induction motor in a better and more efficient way, and is capable of doing important service, which the induction motor cannot do. Mr Faye-Hansen.

Mr. G. W. O. Howe (*communicated*): On page 388 of his paper Mr. Hallo refers to the advantage of the large self-induction of the induction motor as compared with that of a static transformer. As he says, this will result in smaller currents being produced by the higher harmonic electromotive forces. Surely he is here trying to find a virtue in an unavoidable disadvantage. Transformers can be made to have a large leakage reactance, and that very simply, although makers generally strive in the other direction. The reactance of the circuit can be increased to any amount by inserting choking coils between the static transformer and the rotary. The induction-motor part of the motor converter is, after all, a transformer, in which the secondary is made free to rotate, at the cost, however, of a large leakage reactance, and in both cases the effect of this leakage is neutralised by suitable adjustment of the field current. Mr. Howe.

Mr. S. L. Pearce (*communicated*): I have read Mr. Hallo's paper with much interest, and, as regards the performance of motor converters, I have seen no reason to modify the views expressed at Manchester in December, 1906, on Mr. Miles Walker's paper dealing with "Rotary Converters *versus* Motor-Generators." We in Manchester have had a more extended experience of this class of sub-station machine than any one else in the United Kingdom, and we have not regretted our choice. I do not say that we have been entirely free from troubles, but these have been confined to the earlier machines supplied, and have in every case been traceable to poor workmanship, and not to any inherent defect in principle. Without traversing the ground covered by my previous remarks on Mr. Walker's paper, and which will be found in the *Proceedings*, I may state that I am still of opinion that the case for the rotary converter can only be made out on the ground of a slightly higher efficiency, and the extent to which this can be justified may be judged from the official test figures taken at Manchester on three sizes of motor converters:— Mr. Pearce.

Kilowatts.	Full Load.	Three-quarters.	Half.	Quarter.
(1) 250	89·20	—	89·00	85·5
(2) 500	91·50	—	91·00	87·5
(3) 1,500	93·25	93	91·75	86·5

One point in favour of the motor converter has been brought out in our experience, and which weighs very strongly with us in Manchester, and that is its ability to remain in step with the main generating plant in the event of a serious fall of high-tension voltage. It has frequently

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Mr. Pearce. happened on these occasions that the motor converters are the only plant left running on the system, all the rest having dropped out of step. The ability of the motor converter to give leading currents on a system, and so to compensate for otherwise poor power factors, is also extremely useful and valuable.

In connection with the recent Electrical Exhibition in Manchester, there were examples of the three types of converting machinery installed in the Exhibition sub-station, viz., a 500-k.w. motor-generator, a 600-k.w. motor converter, and a 750-k.w. rotary converter. These plants were supplied to the Manchester Corporation by their respective manufacturers on the understanding that they were to be taken over within a stated period for use on the Manchester system. The rotary converter, which is one of the latest types built by the Westinghouse Company, has been recently installed in a large consumers' sub-station, so that we shall have a further opportunity of closely watching the performance of a machine of this class of very recent design, and comparing this with other types of converting machinery.

Mr Bowden. Mr. J. H. BOWDEN (*communicated*): The Poplar Borough Council was, I believe, the first to use this type of machine, and consequently had to suffer to some extent from the experimental stages necessary to the initial installation of the early machines. The troubles experienced, however, were almost entirely confined to the breaking down of the extra high-tension windings, and the occasional flashing over between the commutator brushes—the latter occurring in the event of a heavy earth or short circuit on the low-tension network. The first trouble has been entirely overcome by the fixing of charging gear for the early sets; the later sets have spark-gaps only, and there has been no recurrence of this trouble. The early machines have all been rewound, and it was found necessary to modify the first type of winding. The second-named trouble has not occurred since the fitting of commutating poles. I may state that in the case of the Poplar undertaking all the machines are invariably started from the alternating-current side, although the first five machines were fitted with direct-current starters, greater facility and ease being attained in starting up from the alternating-current side. The points which led to placing the order for motor converters in preference to motor-generators, and the advantages to be gained are, in my opinion, numerous, and include the following:—

1. Less floor space.
2. Considerably increased efficiency at full and low load.
3. Reversibility.
4. Running at unity power factor.
5. Low first cost.
6. Convenience of coupling to 3-wire network, and capability of dealing with out-of-balance load.
7. Other advantages may also be claimed for the absence of slip rings carrying heavy current, and the economy in the high-tension distribution cables.

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Mr. Bowden.

Whatever may be said to the contrary, at the time of ordering our first machines I was of the opinion that engineers generally had certain misgivings as to rotary converters on a 50-cycle circuit; certainly I have no hesitation in saying I had five years ago. I am quite prepared to admit that the rotary converter has made rapid strides during the last five years, and is now, I believe, a thoroughly reliable machine; but on high-frequency circuits I am of the opinion that the motor converter is still the better machine. At that time, from general experience and from information available, the risk of direct-current reversal and the difficulty in the regulation of the direct-current voltage was not as reliable and satisfactory as is now claimed by the makers. I have never regretted installing motor converters, several of the machines having run continuously week in and week out, with only a short stoppage of a few hours every third day for cleaning. With regard to the efficiencies and the results obtained, my experience is that with 500-k.w. sets the highest efficiency is obtained with 70 to 130 per cent. load factor, and with 250-k.w. sets 90 to 110 per cent.

Mr. Baynes.

Mr. S. W. Baynes (*communicated*): For the past eighteen months I have had two 500-k.w. Peebles-LaCour motor converters working at 5,000 volts, 50 periods, 3-phase current, and converting to 440 volts continuous current, with the centre equalising connection to the 3-wire system.

I have found both of these sets to run very satisfactorily, particularly with regard to regulation, which has been markedly superior to that obtained from either our synchronous or asychronous motor-generators under similar conditions.

There is a considerable saving in floor space, an item of no small importance in sub-station work, knowing, as we all do, the very small space that is sometimes available in crowded cities where land is expensive.

I have also a 1,000-k.w. Peebles-LaCour motor converter at the main generating station, which I find particularly useful as a generator of alternating current or continuous current, and on a number of occasions have used this machine to supply alternating current to our sub-station, when it has come fully up to our expectations, both as regards reversibility and regulation.

Mr. Gregory.

Mr. H. W. Gregory (*communicated*): I should specially like to draw attention to the high efficiency of the motor converter at low loads as compared to the rotary, which feature, rendering the machine in practice so valuable in a small lighting sub-station without a battery, may be partly explained by the fact that though the quantity of iron on the rotating part of the motor converter is great, the iron losses, roughly proportional to the square of the frequency, of both rotor and direct-current end occur at only half the frequency of those in the corresponding single rotary converter armature. I should like to ask the author if this is the correct explanation, or whether he attributes the efficiency solely to the absence of higher harmonics in the motor converter running light.

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Mr. Gregory.

Again, the motor converter lends itself better to the adaptation of the synchronous booster than does the rotary converter, inasmuch as the booster armature in the former machine deals only with a part of the current in the direct-current armature, while the rotary-converter booster deals with the whole of the direct-current output. The statement at the bottom of page 392 is at first sight misleading, since as the machine is still running at half synchronous speed, the stator is still transmitting power to the rotor half electrically and half mechanically. It must be remembered, however, that the additional mechanical power not represented in the dynamo element may be driving the booster mechanically to provide the additional rotary-converter effect on the direct-current end. The adaptation of the booster to the motor converter is excellent in practice, efficiency being but slightly impaired, and the arrangement giving a most satisfactory solution of the problem of a very wide direct-current voltage regulation with unimpaired power factor. Lastly, I think the absence of slip rings carrying heavy currents on the motor converter is a point insufficiently appreciated.

Mr. Hallo.

Mr. H. S. HALLO (*in reply*): I shall deal first with the remarks of speakers who have had actual experience with motor converters. Mr. Jenkin speaks of his experience with the motor converters in the Great Western Railway sub-stations, and it is particularly gratifying to hear that my early anticipations have been realised, and that practical experience has more than borne out the theoretical considerations which led to the adoption of motor converters in this instance. The experience of Messrs. Jenkin and Smith shows that motor converters are well suited to the extremely heavy conditions of railway working. The efficiency figures are of importance, and they show that the early converters, which were designed and manufactured before any experience in the actual running of this class of machine had been obtained, have given great satisfaction in this respect. Modern converters, embodying all experience with almost two hundred machines, of the two-bearing type, and running at a higher speed than the Great Western Railway converters, give, as Mr. Jenkin suggests, about 1·5 per cent. higher efficiency. I have very little to add to the full account of the tests, which show with great clearness the whole operation of the electrical plant for the Hammersmith and City Railway, and the lighting of the Paddington Hotel and Station. The reversibility and high overload capacity of the motor converter stand out as prominent features, and I agree with Mr. Bailey that it is very gratifying to learn that this new plant also runs with absolute reliability. Mr. Jenkin refers to the possibility of the motor converter running up to true synchronism of the induction motor, should the field on the direct-current side be broken, and he mentions the satisfactory result of tests carried out to ascertain the safety of the machine at that speed. I may add to this that in actual practice the chance of the converter running up to the high speed is very remote; I would rather expect in this case the alternating current to be cut off by the automatic overload release, but

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a failure of the direct-current field on a motor converter has not yet been experienced. Mr. Hallo.

The beneficial influence of the leading current upon the voltage in the main station is a very interesting feature, which has commended itself to many station engineers.

Mr. Pearce gives the efficiency figures of three sizes of motor converters, and I shall have occasion to refer to these figures when dealing with the question of efficiency. Mr. Pearce further states that the motor converter remains in step with the main generating plant, even in the event of a serious fall of high-tension voltage; the surprisingly large synchronising force of the motor converter has thus proved to be an important point in its favour, increasing the reliability of the plant and ensuring a continuance of direct-current supply in case of serious disturbances on the alternating-current side.

Mr. Gregory is quite correct in saying that the low frequency in the armature and rotor partly accounts for low losses; the absence of higher harmonics is one of the reasons why the difference between the actual commercial efficiency and the efficiency calculated from separate losses is less with motor converters than with rotaries, but with this point of efficiency I shall deal further on at greater length. I also quite agree with him that the absence of slip rings carrying heavy currents is a very important point in favour of the motor converter, especially in view of the troubles experienced by rotary converter manufacturers, and the many experiments made in their works, aiming at a satisfactory solution of the difficulty. Also with regard to parallel running and hunting, points brought up by Mr. La Cour, the modern rotary converter has to be improved a great deal before it is equal to the motor converter.

When reading through the various remarks of Messrs. Jenkin and Smith on the Great Western Railway plant; of Mr. Pearce, who has more motor converters under his control than any one else; of Mr. Bowden, who is chief engineer of the pioneer installation of motor converters in this country; of Mr. Baynes and Mr. Gregory, who have experience with motor converter plant of greater or smaller capacity; and when finally considering the intelligence received about the successful operation of motor converters on the Continent from Professor Arnold, one realises that the motor converter fulfils the high expectations of its inventors, and has become a most important factor in modern sub-station practice. The various advantages of the motor converter, as explained in my paper, result in a combination of reliability and efficiency which cannot be obtained with the motor-generator or rotary converter, so that where high-frequency alternating current is to be converted into direct current, substantial economy can always be effected by the introduction of this type of machine.

I have now to deal with the remarks of those gentlemen who have not had practical experience with motor converters, and in particular I will deal with one point which may have been misunderstood. Mr. Rosenberg is under the impression that I compare, on page 388 of my

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Mr. Hallo. paper, a 6-phase rotary converter, which has to give 30 per cent. wattless current, with the converter part of a motor converter which has to give 33 per cent. wattless current, and then concludes that this comparison is not fair because in that case the motor converter would not supply the same amount of wattless current to the mains as the rotary. I agree that the machines would not be running under the same conditions, but if Mr. Rosenberg will look at page 388 of my paper he will find that I do not make the comparison above referred to, for I say, "When we compare, for instance, the 6-phase rotary converter with 30 per cent. wattless current and the 12-phase motor converter under the same conditions and with $f_c = 0{\cdot}6\, f$, we find that the factor k is the same for both." And this comparison is naturally the proper one. It means that both rotary converter and motor converter are supplying 30 per cent. wattless current to the mains, and this leading wattless current, I may add, is destined to compensate the lagging wattless current taken up by induction motors connected to the same mains.

Now, I quite agree with Mr. Rosenberg that there will be more than 30 per cent. wattless current in the revolving windings, but when he begins to calculate this current he is incorrect, as I shall explain later. The total wattless current in the revolving windings will actually be between 45 and 55 per cent., and this increase of wattless current affects the factor k slightly, but so little that, when writing my paper, I did not consider it necessary to go to the additional complication of calculating k for various values of the magnetising current, and preferred to keep the statement general. Consequently I had to leave out of that passage all reference to the tables on page 387, and I did not state the value of k. Although it is true that for a motor converter with large magnetising current (25 to 30 per cent.) the factor k is slightly smaller than for the rotary, providing the alternating-current wave-form is a true sine wave, I did not consider it necessary to go into this detail, since this slight advantage of the rotary is more than counterbalanced by the extra losses due to larger higher harmonic currents in its windings.

The reason why the comparison was made for 30 per cent. wattless current and $f_c = 0{\cdot}6\, f$, to which Mr. Peck objects, is obvious, for in this case k being equal, all other cases can be judged from this as a standard.

It is also evident that for $f_a = f_c$ the rotary has a slight advantage, which, however, in many cases is again counterbalanced by the effects of the higher harmonic currents, and in this connection it is interesting to compare the efficiencies of rotaries and motor converters under actual working conditions.

Before doing this I will deal with the other remarks of Mr. Rosenberg. He says that in the first part of my paper I never use the expression "rotary converter" for the one part of my machine, but that I always call it a direct-current machine; he further argues that if I had called it a rotary I could not have claimed the many advantages which the motor converter has over the plain rotary. The direct-

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current end, however, is not a rotary, it only works partly (generally one-half) as a rotary, and there is certainly no more reason to call it a rotary than a direct-current machine. Moreover, there are only about sixty lines of print between the introduction of the words "continuous-current machine" and the statement that it works partly as a rotary. At any rate, the direct-current end is a low-frequency machine, and it is the high-frequency rotary which has given, and is still continuously giving, all the trouble, a fact which has caused not only British but also Continental engineers to have such a deep-rooted objection to machines of this description. Mr. Hallo.

Mr. Rosenberg goes on to say that the motor converter with 25 per cent. magnetising current at no load has 40 per cent. magnetising current at full load, just as an ordinary induction motor. Now the motor converter happens to be a synchronous machine, and, as theory tells us, there is not any such increase of wattless current as with the induction motor, and actual tests have amply proved the correctness of this theory. Moreover, the motor converter is usually built with high reactance, and consequently the magnetising current is very low; in fact, machines with 15 per cent. magnetising current are in successful operation.

Mr. Rosenberg has misunderstood my statements. So again with reference to the use of a booster to improve the power factor. The question is that a rotary requires a booster for a comparatively small voltage variation for which motor converters can be built without a booster. For extremely wide voltage regulation a booster may be advisable for a motor converter as well, and it is necessary when power-factor unity is to be maintained under these conditions. Mr. Rosenberg thinks it remarkable that a rotary has been built for the same range of voltage as I give on page 392 of my paper. But there is nothing remarkable in that, as different tappings on the transformer are used for 440 volts and 525 volts, and only 5 per cent. true regulation is obtained. No such additional complication is necessary with the motor converter, and there the full range of voltage from 420–550 volt—that is, 30 per cent. true regulation—can be obtained. Moreover, a similar practice could be followed with motor converters by making tappings on the stator windings, that is, shifting the neutral-point by cutting out a suitable number of turns, a method protected by letters patent held by the inventor of the motor converter, but on more than one occasion central station engineers have condemned this practice of making tappings on transformer windings, and certainly there can be no doubt that it is more satisfactory to do without them. With our present practice the motor converter can be switched over far more quickly from the lighting busbars to the traction busbars, or *vice versâ*, than is possible with the rotary with transformer tappings.

Mr. Peck considers it a fallacy to state that the high-frequency rotary cannot be made to run satisfactorily, but he omits to say that with the introduction of such machines one cuts down the limit between a stable and an unstable and unsatisfactory machine to a

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Mr. Hallo. very fine point. Even although a few high-frequency rotaries may be made to give some satisfaction in actual practice this still remains the exception and not the rule, and stable running in these cases might possibly be upset by the introduction of more rotaries of the same design in the same station, or by changing the plant at the generating station, when phenomena of resonance may take place, such as mentioned by Mr. La Cour in his contribution to the discussion.

Mr. Seabrook's argument that a difference of efficiency of *one* per cent. is so important that it would not pay him to run motor converters with a day and night load, even if they were supplied free of charge, seems strange, as he has nine stations with motor-generators and three with rotaries. One cannot help wondering how under these conditions motor-generators with 4 to 5 per cent. lower efficiency can pay when only run during the daytime.

With regard to floor space I can but repeat my statement that there are several installations, where by the adoption of motor converters plant of considerably greater capacity has been put into the space available than would have been possible with rotaries. The argument that transformers do not take up any room at all because they can be placed in the basement is a fallacy—in fact, the whole motor converter could be put in the basement. The only rational way of looking at this matter is to consider the floor space taken up by the motor converter as against the rotary and its accessories.

On the question of output, in spite of the fact that the motor converter was a new type of machine and that many engineers hesitated to instal converters on their mains before their advantages had been proved in actual practice, the output of motor converters is still considerably more than that of rotaries, which alone is sufficient evidence of the rapidity with which the motor converter has gained popularity through its inherent merits and despite slightly higher first cost. It would be interesting to know how many rotaries of less than 50 cycles ($33\frac{1}{3}$ and 40) are included in Mr. Peck's term "high-frequency rotaries." The actual output of 50-cycle 500-volt rotaries in this country falls very much short of 40,000 k.w., and in view of the fact that the motor converter is now so widely known it is not probable that the high-frequency rotary will find many advocates in future.

With regard to Mr. Peck's remarks on the starting up of motor converters, it will be found that it is far easier to synchronise on the voltmeter on the starter of a motor converter than by means of a lamp or synchroscope with the rotary. And this is obvious, as the motor converter is actually connected to the alternating-current mains and follows the fluctuations of frequency, whereas a rotary is not so connected, and thus cannot possibly follow such fluctuations. The result is that it often happens when synchronising rotaries one just misses a shot, as it is technically called. As a rule neither the rotor resistance nor the field rheostat of the motor converter are touched during the starting period, but even if any adjustment should be required it would be a mistake to operate both, as Mr. Peck suggests.

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Mr. Jenkin's statement that it is necessary to watch the building up of the direct-current field naturally refers to first start; later on it is not necessary when the machine is permanently connected for self-excitation. Mr. Hallo

With regard to the question of efficiency, Mr. Peck suggests that the curve on page 390 is impossible of realisation by calculation of separate losses. This is incorrect, as this efficiency curve shows real figures, as obtained in actual practice.

I may here refer to the efficiency figures given by Mr. Pearce in his contribution to the discussion, and it will be seen that these particular figures would be still more impossible of realisation according to Mr. Peck's method of calculation. The efficiency at full load of the 500-k.w. set is slightly less than given in my paper, owing to the fact that this particular machine was built for a 30 per cent. voltage regulation. At quarter load the efficiency is, however, substantially higher—in fact higher than can be obtained with a rotary and its transformers. I may mention here that tests carried out in the Manchester Corporation sub-stations showed the remarkable difference of 12 per cent. in the efficiency of 250-k.w. motor converters and motor-generators at quarter load.

In his communicated remarks Mr. Peck states that the separate loss method is the most accurate one for obtaining efficiencies. Now, it is quite true that with the in and output method the inaccuracy of instruments to the amount of about 1 per cent. has to be accepted. But there is no reason why this error should always be accumulating, that is in opposite sense for alternating-current and direct-current instruments. Moreover, the measured efficiency may just as well be too low as too high, and in fact, when one takes a great many readings and repeats this for many machines, there is no reason why the average figure should not be a very good approach to the real efficiency. With the separate loss method, however, one always gets too high figures, and this is especially the case with rotaries, where the higher harmonic currents cause considerable losses and have to be paid for by the station engineer.

There is no doubt whatever that the efficiency of a 550-k.w. rotary converter under actual running conditions is about 2 per cent. less than Mr. Peck calculates from his separate losses, and in this connection it is significant that many engineers have stated that the high efficiencies claimed by the manufacturers of rotaries are not realised in practice. This is not surprising when they are obtained from the separate loss method, which is, for the reasons stated before, a peculiarly unsuitable method to determine the actual efficiency of a rotary, however admirable it may be for obtaining hypothetical and inviting figures.

The Hopkinson method of determining efficiencies, a method which is universally known and acknowledged to give the most accurate results, cannot be used for rotaries, one sufficient reason being the instability of the machines under these conditions. With motor converters this method has been followed, and it has shown

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Mr. Hallo.

over and over again that the efficiencies given in my paper are actually realised. I can answer in the negative Mr. Peck's suggestion that special Stalloy steel was used.

One point I have still to refer to. According to Mr. Peck, 6,000 volts is the highest voltage for which it is safe to wind high-tension windings, but in fact for sizes over 250 k.w. it is quite safe to go up to 10,000 volts and over. I admit that there was a time when electrical manufacturers had considerable trouble in making extra high-tension windings absolutely safe, but fortunately considerable progress has been made, and such stationary high-tension windings can now be made just as safe as revolving low-tension windings. The firm I am connected with have perfected such windings to such an extent that no breakdown has occurred on the stator of any motor converter with the style of winding adopted about three years ago, and which is now always used. These windings are giving satisfaction on 10,000-volt mains.

Mr. Howe, for some unexplained reason, considers the large reactance, which is usually given to the induction motor of a motor converter, a disadvantage. Mr. Faye-Hansen, however, states as an advantage that the transformers of rotaries can be given an equally high reactance. For a given load and direct-current voltage, a rotary with low reactance transformers cannot be made to give the leading current required under different conditions of the network. A certain leading current will correspond to every alternating-current voltage and frequency, and in order to regulate this leading current a booster is required, just as with a motor converter. Mr. Faye-Hansen further states that a rotary with low reactance transformers running inverted has a better voltage regulation on the alternating-current side than a motor converter, but he omits to state that a special exciter is required to keep the rotary from racing when wattless currents are taken from the machine. A motor converter does not require such an exciter, and when provided with a booster instead, it has an infinitely better regulation than the rotary. He further states that if no special reactance is required for other purposes, the reactance of the transformer can be made so as to get the greatest stability of running. Just so; in all other cases where such special reactance is required the stability of running has to be sacrificed, and many an engineer has experienced this to his great sorrow and disappointment. This is another advantage of the motor converter; no such sacrifice is required, because the hunting trouble is unknown. Further, it is not correct that the reactance of the motor converter is controlled by the design of the machine, as there is a special method of obtaining this large reactance without interfering with the flux and number of turns, this method having the additional advantage of giving a low magnetising current, with an overload capacity corresponding to a low reactance.

I think that the following table gives an impartial review of the cases in which the various types of converting plant are to be used:—

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USE OF VARIOUS TYPES OF CONVERTING MACHINES. Mr. Hallo.

Periodicity.	Conversion: Alternating Current / Direct Current or Direct Current / Alternating Current	Motor Converter.	Motor Generator.	Rotary.
Under 25 cycles	Alternating current / Direct current	No	Only for large voltage variation	Yes, except for large voltage variation
	Direct current / Alternating current	No	Yes, synchronous	Only for power-factor unity
25 to 40 cycles	Alternating current / Direct current	Yes, except for voltage regulation over 30 per cent.	Only for voltage regulation over 30 per cent.	Yes, except for voltage regulation over 10 per cent.
	Direct current / Alternating current	Yes, except for power factor under 0·8	Only for power factor under 0·85	Only for power-factor unity
40 cycles and over	Alternating current / Direct current	Yes, except for voltage regulation over 30 per cent.	Only for voltage regulation over 30 per cent.	No
	Direct current / Alternating current	Yes, except for power factor under 0·8	Only for power factor under 0·85	No

Of course, with such a complicated subject no full information can be put in such short tabular form; considerations of boosters, etc., had to be left out. In special cases it will be necessary to study the subject more deeply, and I hope that my paper will facilitate such study.

One point strikes the observant reader of the discussion of this paper, which was written with the object of bringing the theoretical side of the motor converter more into the foreground, seeing that its applications had become so wide and varied. No special chapter under the heading "Comparison of Various Types of Converting Plant" was introduced, and only in a short introduction were the other types of converting plant referred to with their advantages and disadvantages. It cannot be wondered at, however, that the discussion centred itself round this point, which is of such eminent importance from the practical point of view.

The PRESIDENT: I have now the pleasure of proposing a hearty vote of thanks to the author for this paper. The President.

The vote was carried by acclamation.

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EXTENDING THE LIMITS OF POWER TRANSMISSION.

AS APPLIED BOTH TO LONG-DISTANCE TRANSMISSION OF POWER AND TO POWER COMPANIES' AREAS.

By A. M. TAYLOR, Member.

(*Paper received from the* BIRMINGHAM LOCAL SECTION, *December* 18, 1908, *and read at Birmingham on March* 10, 1909.)

The present paper consists merely of a few brief notes and suggestions, and does not attempt to deal with the subject in a comprehensive way, the object being to draw attention to certain possibilities in the way of commercial developments that, as far as the author is aware, have been somewhat overlooked.

The question of long-distance power transmission will first be considered.

I. OVERHEAD LINES.

The cost of long-distance 3-phase overhead lines may be divided up into the cost of copper and the cost of supports.

The capital cost of copper at £60 per ton, employing an initial voltage of 270 volts per mile of line, a current density of 250 amperes per square inch, and a combined drop of 35 volts per mile, amounts to roughly £20 per effective kilowatt transmitted, assuming power factor equal to 80 per cent.

On a 100-mile line this would mean an initial voltage of 27,000, a total combined drop of 13 per cent., and a capital cost of £20 per kilowatt transmitted, which, on a 25 per cent. load factor, and taking interest, sinking fund, maintenance, and depreciation at 25 per cent. per annum, would mean a charge of roughly ½d. per unit transmitted.

By increasing the length of line to 122 miles, the line voltage being kept at 27,000, the capital cost per kilowatt would be increased to £30 per kilowatt transmitted.

So much for the copper part of the line; now for the supports. For light lines we may, perhaps, take £200 per mile as a minimum figure, while for heavy lines £500 per mile may be easily reached, excluding wayleaves.

Assume the power delivered to receiving end of line to be, say, 10,000 k.w.; this would require the heavier line construction, but, on the other hand, the cost per kilowatt would come out less than if we took a much lighter line, suited to the cheaper posts and insulators.

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A line 100 miles long would, therefore, cost £50,000, or £5 per kilowatt transmitted for the capital cost of poles and insulators.

The smaller line, for, say, 1,000 k.w., would have cost £20 per kilowatt transmitted, for the same items.

It will be evident that on copper figures, and with a limit of 27,000 volts and 10,000 k.w., 100 to 120 miles is about the economical limit for the bulk of the transmission, and 50 miles with 1,000 k.w., except where coal is very dear.

In Fig. 1 a curve is given connecting copper cost per kilowatt transmitted with length of line, for a given percentage volt drop and a given initial voltage.

In Fig. 2 is given the cost per kilowatt for the supports, plotted with length of line, for different kilowatts transmitted.

It will be granted that any means which would halve the cost of the

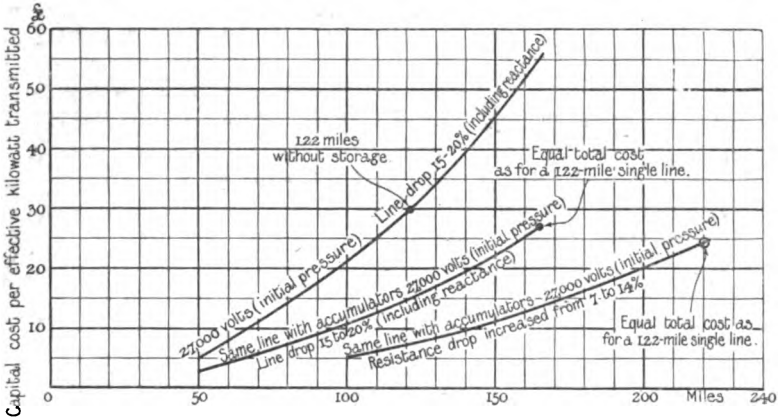

FIG. 1.

copper in the line would virtually increase by some 30 to 40 per cent. the possible distance of supply (in bulk), and thus be extremely useful in bringing the water-power—which is mostly in inaccessible spots—to the big towns, where there is a demand for the power.

It will probably be also agreed that in many cases, especially where the line has to traverse mountainous districts for many miles, and is subject to interruptions through difficulties of inspection, etc., it becomes desirable to duplicate both poles and wires, and the cost of the line is thereby doubled.

The author's proposal is that electrical storage on a large scale should be carried out at the distributing centres, the reliability of the line being thereby increased to an extent that would warrant a second line being dispensed with. At the same time, he hopes to show that it is not necessary to trade upon the latter assumption in order to show a case for storage.

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The batteries would be arranged to take up 50 per cent. of the peak, thereby halving the copper costs for the line.

In the case of a 10,000-k.w. 122-mile transmission with a single line, it will be found that, without raising the E.M.F. or increasing the line drop, the radius of transmission can be extended to 165 miles for the same total capital cost of 30 + 6 = £36 per kilowatt transmitted.

To cover this distance, *with a single line*, and with the E.M.F. limited to 27,000 volts, would have cost, without storage, some £63 per kilowatt transmitted. The storage scheme is thus some £27 per kilowatt the cheaper, as far as the line is concerned.

If the 122-mile line above considered had been run in duplicate, as regards the copper, only one line of poles, however, being provided, the

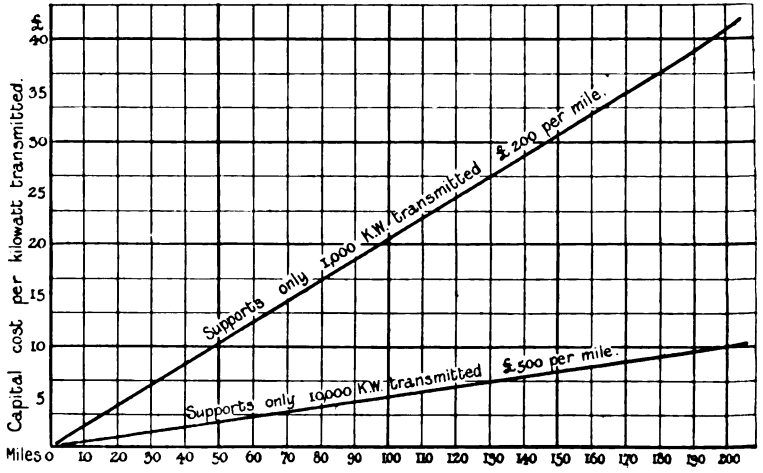

FIG. 2.

radius of transmission could have been extended from 122 miles to about 230 miles without increasing the capital costs of the line.

It will, no doubt, be objected that the author has taken too low a voltage, and that 50,000 volts might with advantage have been considered. But against this it may be said that the higher voltage brings its own disadvantages, and that, where the line has to pass through damp or smoky districts, the higher voltage would be risky.

Another point that makes for the reduction in voltage is the fact that the distributing part of the line not infrequently equals the transmitting part of the line in length or is worked at a lower voltage (as, for instance, the St. George's and Fabrezan transmission, referred to later). Consequently, the total cost of the line and distributors will really be that of a line working at an average voltage much below that of the initial voltage ; and any saving effected on the first part of the

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line is, in part, compensated by the cost of the extra step-down transformers and the higher insulation wanted throughout the high-tension section.

In the example already considered, the resistance loss would be 8 per cent., and with a current density of 400 amperes per square inch, this might be run up to 16 per cent. With a battery at the distant end of the line a much greater resistance drop than 8 per cent. could be allowed in the line without the regulation of voltage being seriously affected; and it will probably be conceded that, in most cases, a greater resistance drop will be considered preferable to the risks introduced by increasing the voltage.

One disadvantage of the lower voltage would be the considerably increased reactance on such a line; but the reduced generator capacity caused by this can be eliminated at moderate cost, and the author has definite proposals to make in this connection, but to touch upon these now would unduly lengthen the present paper.

It will, of course, be understood that, whether 50,000 volts or 30,000 volts be employed, the percentage increase in the length of the line effected by the use of accumulators, for a given total copper cost, remains unaltered; but the item for supports is evidently greater, in proportion to that for the copper, with the higher voltage, and somewhat reduces the length that would otherwise be permissible.

If, as suggested above, we take account of the much greater facilities for regulation provided by the employment of storage at the receiving end of the line, it will be found possible to double the resistance drop in the line and thus roughly to double the distance of transmission. Thus, the 122-mile single line considered in Fig. 1 *could be lengthened to* 220 *miles*, without any additional cost being incurred on the line, by the employment of storage; while, had the line been originally laid out in duplicate (as far as copper is concerned), it could have been extended to 304 miles for the same total cost in copper and supports.

The author suggests that, considering the desirabilty of being able to shut down one half of the line copper for repairs to insulators, etc., it will often be found advantageous to provide the spare copper circuit, where there is no storage. With storage at the consumer's end of the line, it is, of course, possible to deaden the line at certain times of the day without interrupting the supply.

The batteries and auxiliaries required for storage can in most, if not in all, cases be provided for out of the saving in generating plant, step-up and step-down transformers, turbines, head works, and buildings, only half the horse-power being needed that would otherwise be required.

Where the heads of water are low, the costs of the plant and head works run up rapidly, as will be seen from Table A, which gives the costs stated to have been incurred in some of the Swiss water powers, the average figure being about £73 per kilowatt.

On falls such as these the saving in generating plant and head works would suffice to extend the line to no less than 210 miles without

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increasing the total capital cost of the scheme, as compared with a single-line 122-mile scheme without storage. The further extension, due to saving in line copper, has of course to be added.

The cost of batteries to deal with a load curve of the type shown in Fig. 4 would be about £10 per kilowatt, to which about £3 10s. per kilowatt must be added for auxiliaries and accessories, on alternating-current systems.

Where the batteries cannot be paid for out of the saving in generating plant, they must, of course, be paid for in part out of the line savings; *i.e.*, the full benefit of the increased lengths above indicated, cannot be obtained.

TABLE A.*

	Cost of Power Station (Exclusive of Lines).	Horse-power Installed.	Horse-power Demanded.	Cost per Horse-power Demanded.	Cost per Kilowatt Demanded.
	£			£	£
La Goule ...	57,300	3,650	1,700	34	48
Geneva ...	280,000	12,000	8,100	26	37
Lintnal ...	16,500	1,000	510	32	46
Hauterive ...	260,000	7,200	4,900	54	77
Mont Bovoa ...	232,000	5,400	2,650	88	125
Kubelwerk ...	270,000	4,200	3,000	69	98
Fihl	104,000	2,000	1,960	52	74
Wynan ...	120,000	5,750	2,800	43	61
Hagneck ...	216,000	5,200	2,700	80	114
Beynan ...	341,000	11,700	8,450	40	57

The advantage of having a standby at the consumers' end of the line, equal to the maximum capacity of the whole scheme for short periods, is one which, of course, cannot easily be expressed in monetary value, but is nevertheless very great.

The savings on a large power transmission scheme by the introduction of storage are not confined to the items above considered, such fixed charges as wages, management, taxes, water-power purchase rights, etc., being *all* reduced with the reduction in the rated size of

* *Electrical Engineer*, vol. 41, p. 452, 1908.

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the generating station and line ; and these would, of themselves, the author estimates, alone more than pay for the cost of maintenance of the batteries and auxiliaries.

II. Underground Cables.

The author believes that similar arguments to the above will influence those power companies which have to cover large areas, in the direction of putting down accumulators at the distributing centres, or offering their customers such terms for current during restricted hours, for charging purposes, as will induce them to put down accumulators themselves.

Take the case of a small town on the outskirts of a power company's area. If the power company has to run a special feeder out to that town, it may easily happen that the costs of that feeder, especially

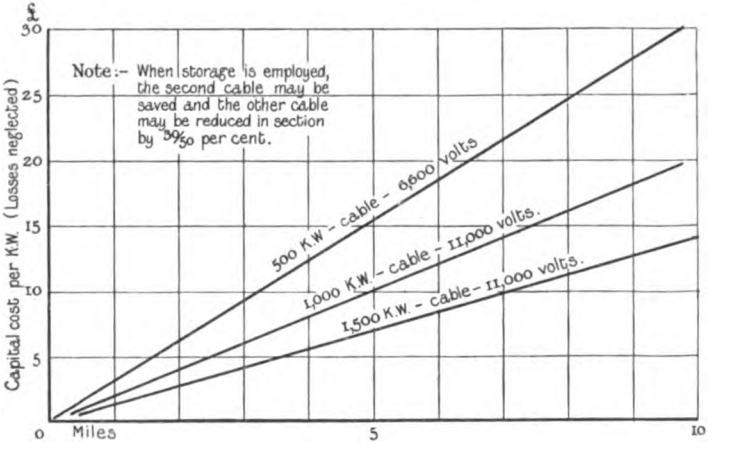

Fig. 3.

if in duplicate, may run into £10, or more, per kilowatt of maximum demand, and, if the load factor is low, this is a serious item.

In this case the savings in fixed charges at the generating station, as the author has shown in a recent article,* would alone pay for the cells, and the saving in the feeder could be put down as clear profit.

Or, again, a power company covering a very large area and confined, by lack of facilities for cheap power production, to one part only of this area for its generating station, might find it practicable to reduce materially the costs of its general transmission and distribution system, as well as improve the reliability thereof, by employing large batteries in its own sub-stations.

To emphasise the importance to a power company of the saving that might thus be effected in underground feeders, the author has

* *Electrician*, vol. 62, p. 305, 1908.

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plotted the costs for duplicate underground feeders for three different sizes such as would be run to a small town. These costs are plotted in Fig. 3. They are taken from curves given in a paper by Mr. J. F. C. Snell.*

It will be seen from these figures that if a power company had to run a special feeder 10 miles long to pick up the load of a small town, it would cost them, if the load was not above 1,000 k.w., something

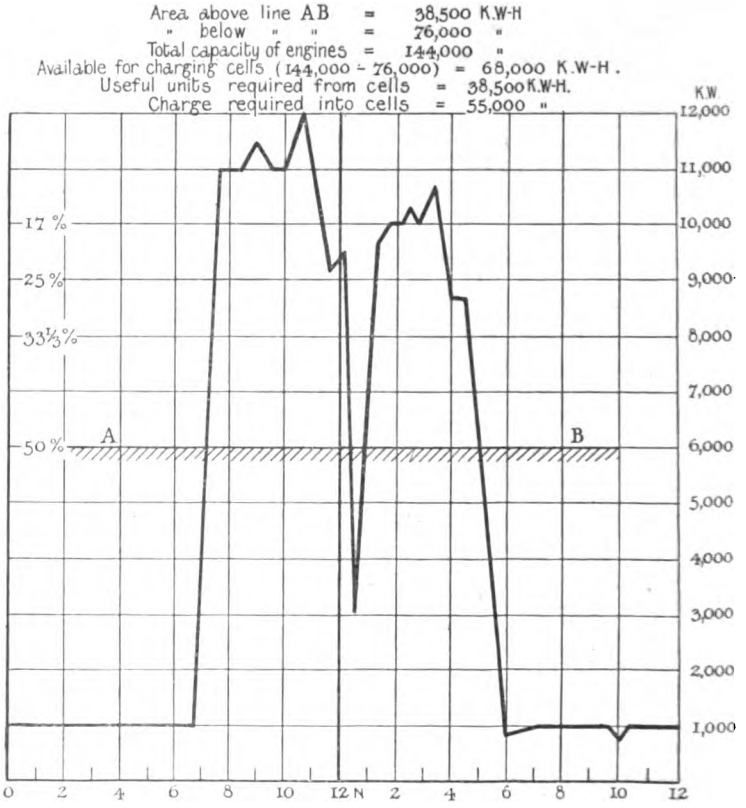

FIG. 4.

like £20 per kilowatt, if the feeder was laid in duplicate. Much greater reliability of supply could, with storage, be obtained with a single feeder of only 50 to 60 per cent. of the sectional area of one of the others, the capital cost in such case being not much more than half. The battery costs need not be debited to the feeder, for they will be saved over again in other directions, and the result is a clear saving in feeder outlay of £8 to £10 per kilowatt—enough in some cases to make the difference between profit and loss.

* *Journal of the Institution of Electrical Engineers*, vol. 40, p. 288, 1908.

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The diagram will also serve to emphasise the importance of any saving which a power company may make in its general transmission system, such as it would do by installing battery sub-stations at suitable points.

In this connection the author would like to call attention to, in his opinion, a somewhat prodigal provision for generating stations made by several of the power companies, as indicated in the maps of areas of these companies, published in the *Electrician's* Annual Tables (accompanying the issue of January 1st of that paper).

A glance at these maps will show that generating stations are projected, at the following distances apart, in the case of :—

North Metropolitan Electric Supply Company		9 miles apart.
South Wales Electrical Power Distribution Company		12 ,,
Clyde Valley Electrical Power Company ...		16 ,,
Yorkshire Electric Power Company	(*a*)	12 ,,
	(*b*)	18 ,,
Fife Electrical Power Company	(*a*)	6 ,,
	(*b*)	13 ,,
Lothians Electric Power Company	(*a*)	7 ,,
	(*b*)	12 ,,
Leamington and Warwick	(*a*)	9 ,,
	(*b*)	12 ,,
Derbyshire and Nottingham	(*a*)	8 ,,
	(*b*)	15 ,,
Cumberland E.P.G. Company		8½ ,,
Gloucester E.P. Company		13¼ ,,
Somerset E.P. Company		10 ,,
Kent E.P. Company	(*a*)	12 ,,
	(*b*)	26 ,,

NOTE.—(*a*) signifies possible alternative sites for station ; (*b*) signifies do not appear to be alternative sites.

Diagrams are given of the stations scheduled or equipped by the first six companies (see Figs. 5 to 10).

In view of the saving, both in capital cost and in working expenses, of large stations as against small ones—the saving in the former being given by Mr. Addenbrooke recently as amounting to £17 per kilowatt of maximum demand, exclusive of distribution, as between 2,500 k.w. and 40,000 k.w.—the author thinks that sufficient attention has perhaps hardly been paid to the desirability of covering a large area from a given power station, even, if necessary, at rather higher costs for distribution.

Mr. Addenbrooke, it is true, shows *reduced* costs for distribution with the larger stations, but this can only be, the author thinks, on the assumption that the larger stations were put down in the more densely populated districts, and required less cable per kilowatt connected.

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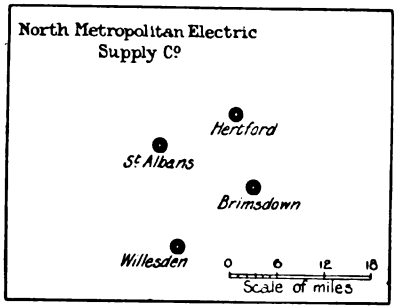

FIG. 5.

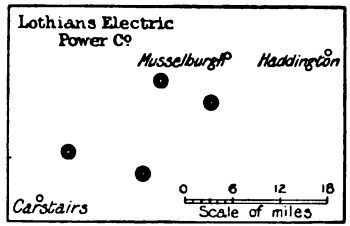

FIG. 6.

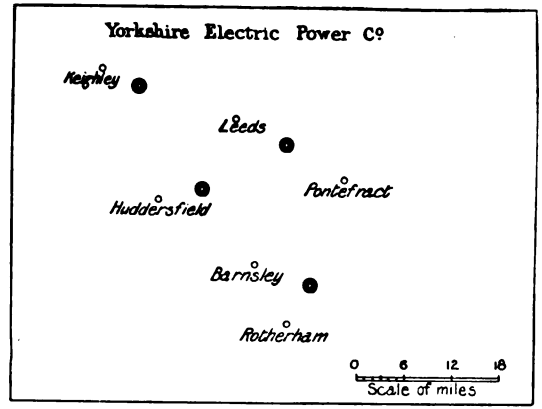

FIG. 7.

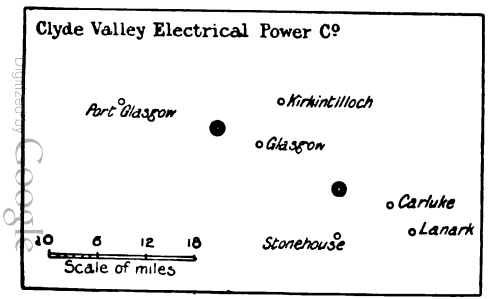

FIG. 8.

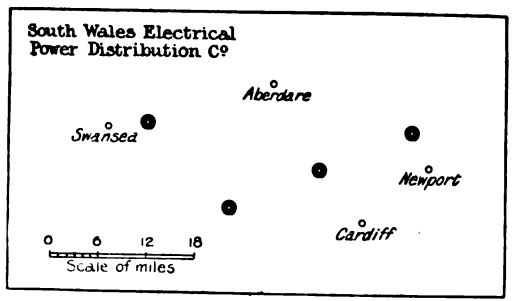

FIG. 9.

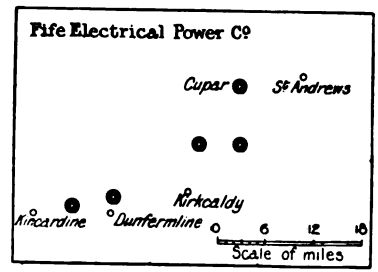

FIG. 10.

It is found that, with 10,000 volts and 1,000 amperes per square inch, the resistance drop amounts to 7½ per cent. per 10 miles. Since, in the early stages of the scheme, it would be most unlikely that the current density would average, throughout the length of the cable,

Analysis of Section Marked B *in Fig.* 11.

Element of Route.	Decrement of Load.	Load on Element.	Amperes at 10,000 Volts.	Length in Yards.	Current Density.	Per Cent. of Drop.
	Kilowatts.	Kilowatts.				
No. 1	800	1,800	108	2,053	1,000	0·87
„ 2	50	1,000	60	1,760	555	0·41
„ 3	200	950	57	2,640	527	0·59
„ 4	200	750	45	352	417	0·06
„ 5	200	550	33	800	306	0·10
„ 6	50	350	21	1,320	194	0·11
„ 7	100	300	18	3,226	167	0·23
„ 8	200	200	12	350	111	0·02
	1,800	—	—	12,501	—	2·39

Analysis of Section Marked C *in Fig.* 11.

No. 1	50	1,650	99	1,760	1,000	0·75
„ 2	200	1,600	96	782	970	0·32
„ 3	450	1,400	84	2,110	848	0·76
„ 4	400	950	57	440	576	0·11
„ 5	100	550	33	2,465	334	0·35
„ 6	100	450	27	3,190	272	0·37
„ 7	50	350	21	3,270	212	0·29
„ 8	200	300	18	390	182	0·03
„ 9	100	100	6	295	61	0·01
	1,650	—	—	14,702	—	2·99

Analysis of Section Marked D *in Fig.* 11.

No. 1	400	2,000	120	4,840	1,000	2·06
„ 2	100	1,600	96	390	800	0·17
„ 3	750	1,500	90	390	750	0·12
„ 4	750	750	45	220	375	0·03
	2,000	—	—	5,840	—	2·38

anything higher than 500 amperes per square inch—take, for instance, the (existing) Power Company's scheme illustrated in Fig. 12—the drop on a 10-mile radius may probably be taken as not exceeding 3¾ per cent. It would therefore look as though it would have been safe to space the stations, say, 18 to 20 miles apart instead of 10 to 12

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miles apart, as obtains in several cases in the above table, and to put down transformer sub-stations, where the voltage could be boosted up if necessary.

The author suggests that, where accumulator sub-stations are put down for dealing with the peak of the load, the load transmitted at the time of the peak can in some, if not in most, cases be reduced to one-half, and in others may be reduced to nothing.

This may be taken advantage of, either to cut down copper and save in capital outlay in the transmission line, or to double the *length* of that line and increase the distance between generating stations from 18 miles to 36 miles. It will be granted that the voltage regulation at the boundaries of the system will be so improved by the employment

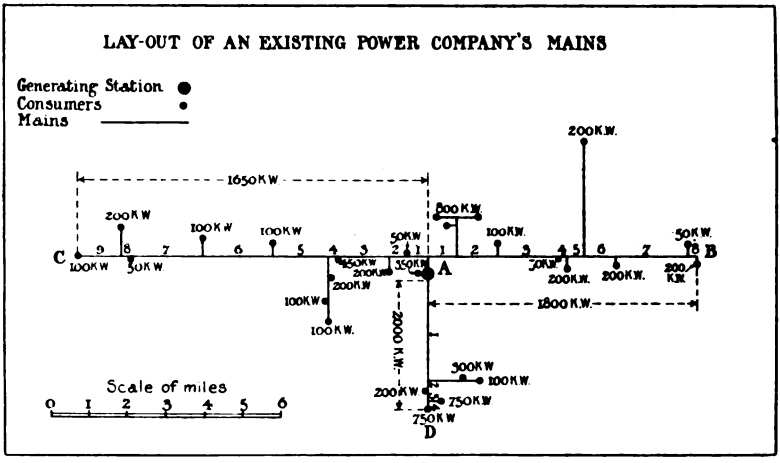

FIG. 11.

of the battery sub-stations that a greater loss in transmission may be allowed, and thus sufficient copper be saved to double the length of the copper conductor and pay for the cost of insulating, armouring, and laying the additional length.

It will also be granted that such an extension of the radius of supply would, in many cases, represent quadruple the load on a single station, and enable companies supplying sparsely populated districts, or large areas, to avail themselves of the saving in the capital invested in, and in the working expenses of, the generating station, which Mr. Addenbrooke very rightly pointed out can be made.

GENERAL.

It will, no doubt, be readily conceded that any means that will permit of a battery installation on either a water-power scheme or

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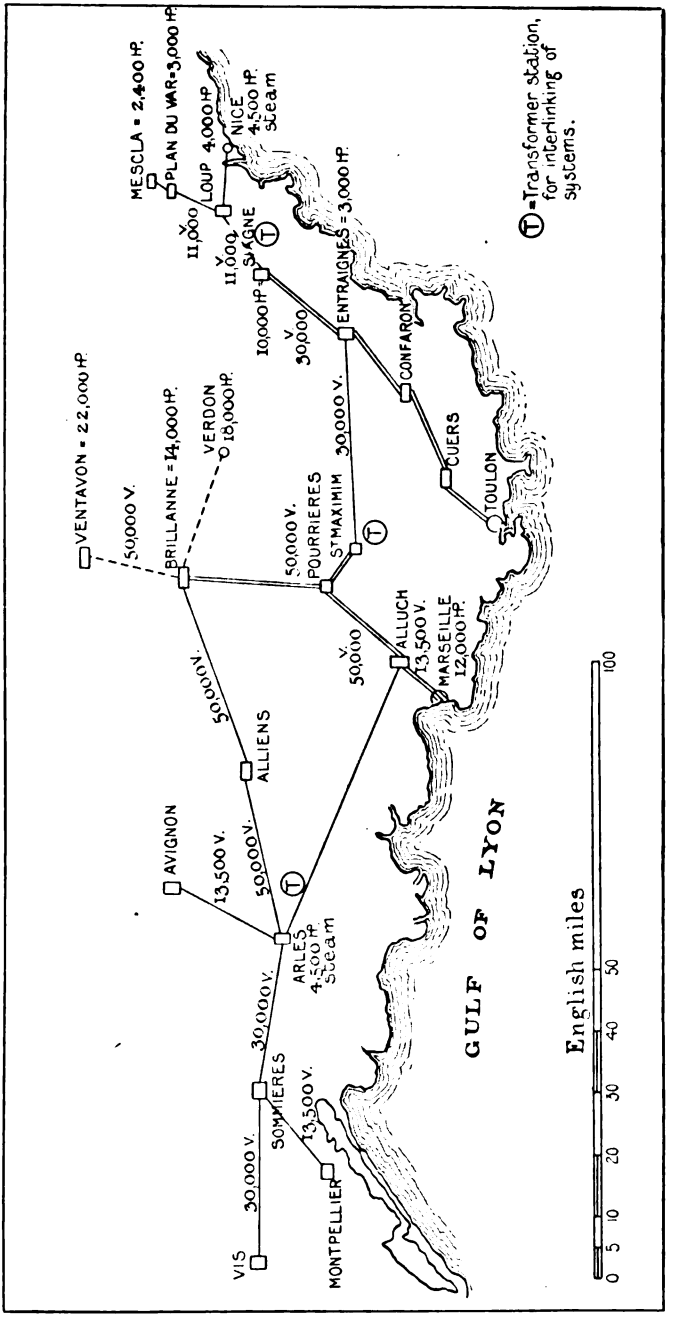

FIG. 12.

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a power company's scheme being commenced with a minimum of outlay and a maximum of reliability is to be welcomed. When put down on the lines usually followed, accumulator batteries do not readily lend themselves to extensions, without a great sacrifice in floor space and a considerably increased capital expenditure above what the author considers necessary.

In accumulator sub-stations with alternating currents, there is not much experience to go on in this country; but in the United States considerable attention is apparently being given to the use of rotary converters—whether of the "split-pole" type or of the "booster" type

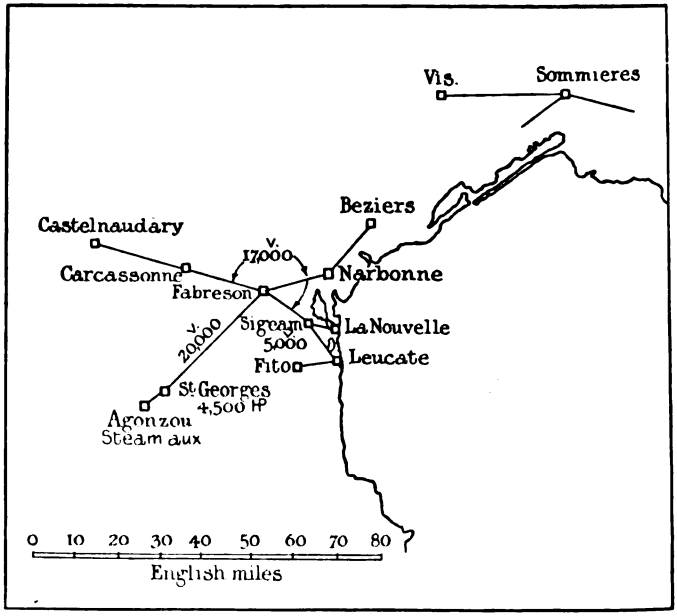

FIG. 13.

—in conjunction with storage batteries on alternating-current systems. The author has proposals of his own to make in this connection; but prefers to wait till they have been put to the test of experience before bringing them up for discussion at this Institution.

It might be thought at first sight that the energy losses on an alternating-current scheme would be serious, but, on a water-power scheme, the cost of each unit of electricity put into the battery, if put in at suitable times, is only of the order of 0·05d.; consequently, neither the efficiency of the rotary converter nor that of the battery is so important as to weigh seriously in comparison with the charges on the line and generating plant.

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High-Tension Power Transmission in Europe.*

A recent issue of the *Electrotechnik und Maschinenbau* (vol. 26, p. 1058, 1908) gives the following list of undertakings in Europe whose transmission voltage exceeds 30,000 volts :—

	Voltage.	Date of Opening.	Capacity.	Length of Transmission Line.	Contractors.
			Kilowatts.	Kilometres.	
Heimbach (Ruhrtalsperren-Ges.), Aachen	34,000	1904–5	3,090	143	Siemens-Schuckert
Munich (Moosburg)	50,000	1906–7	4,000	56	Siemens-Schuckert
†Hamburg—Altona	30,000	1906–7	5,600	14·6	Siemens-Schuckert
Kykkelsrud, Norway	50,000	1907	3,000	42	Siemens-Schuckert
Sociedad Hydroelectrica Iberica, Spain	33,000	1903–5	10,000	200	Siemens-Schuckert
Lagunas de Ruidera, Spain	30,000	1903–6	1,050	—	—
Sociedad Hydroelectrica Espanola Molinar	66,000	In course of erection	25,000	250 to Madrid 120	Siemens-Schuckert
Madrid	30,000	1901	3,000	—	Kolben & Co.
Zamoro, Spain	40,000	1906–7	3,300	40 to Valladolid	Alioth & Co.
Sociedad Hydroelectrica de Guadiero, Spain...	50,000	1906–7	4,500	130	Maschinenfabrik Oerlikon
Bilbao, Spain	33,000	—	3,460	120	—
Caffaro, Lombardy	40,000	1906	10,000	50	Maschinenfabrik Oerlikon
Montereale an der Cellina, Lombardy	36,000	1905	7,000	33 to Venice	Brown, Boveri & Co.
Gromo, Lombardy	40,000	1906	3,000	34	Brown, Boveri & Co.
Tusciano, near Clevano	30,000	—	7,000	—	Westinghouse
Bournillon, France	35,000	1905	1,000 H.P.	—	—
La Plombière, France...	57,	1906	3,000	200	Comp. de l'Industrie Électrique de Geneva
Saint-Cézaire, France	30,000	1906–7	5,700	60 110	Thomson-Houston
Durance Station, Marseilles	50,000	—	15,000	—	—
‡Moutiers—Lyons	57,000	April, 1906	4,100	130	Comp. de l'Industrie Électrique de Geneva (Thury System)

* *Electrician*, vol. 62, p. 509, 1909. † Single phase. ‡ Direct current.

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On a power company's distribution scheme, where the power is generated by steam, the cost of the energy put into the cells for charging purposes is only of the order of 0·10d. per unit; so that here again the efficiency of the rotary converters and of the battery is not so important as might be thought.

To engineers interested in the general question of batteries used in the sub-stations of alternating-current and direct-current systems to take up the peak of the load, the author would here state that some of the points raised in this paper will be found more fully discussed in a recent article,* and in a paper read by him before the Municipal Electrical Association on July 3, 1908, entitled "Alternating-current Accumulator Sub-stations."

Fig. 12 shows a plan of the system of the Société Energie Electrique du Littoral Mediterranée; and for further particulars of these systems members are referred to the article by Dary. †

A plan of the area fed by the water-power transmission system of the Société Meridionale de Transport de Force is given in Fig. 13.

Discussion.

Mr. Chappell.

Mr. W. E. Chappell: I regret that I am unable to agree with some of the statements put forward by the author of the paper. He estimates £500 per mile as a price which might easily be reached for the supports of a heavy overhead line. It may be interesting to know that for £293 per mile it is possible to supply and erect the steel towers of a thoroughly up-to-date line for transmitting 10,000 k.w. at a pressure of 40,000 to 60,000 volts. This price also includes the cost of the line insulators on voltages up to 60,000. It would not be policy to employ wooden poles, as the depreciation is very great, being about 10 per cent. on the poles, 12½ per cent. on the insulators, and 5 per cent. on the copper. In a number of installations in the United States it has been the practice to supply transformers which can be adapted for either 40,000, 50,000, or 60,000 volts, and to start the transmission at 40,000 volts. As the demand for energy increases, the transmission voltage may be raised. The author states that by employing a battery it would be possible to cut down the copper by 50 per cent.; but this is somewhat doubtful, and, furthermore, in putting up overhead lines, it is not so much the carrying capacity that determines the size of the cable as the length of span, the stresses due to wind pressure, and other conditions. In the United States there are five systems in operation similar to that proposed by the author, and the results obtained by the working of these systems have not been as good as the originators hoped. One of the systems has been abandoned, two of them are working fairly well, and the remaining two are anything but satisfactory. With reference to the author's statement that a battery would enable a portion of the line to be completely shut down for repairs, this is only possible if there are no consumers on that particular section of the line; and in supplying

* *Electrician*, vol. 62, p. 305, 1908.

† *Electrical Review*, vol. 62, pp. 533 and 703, 1908.

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energy in bulk, the demand on a battery would be so great that it could not continue the supply for a longer period than two or three hours. Mr. Chappell.

Mr. J. P. KEMP: I agree with Mr. Taylor that there is a good deal to be said for the adoption of accumulators, one point which appeals to me being the very high emergency value of a battery and the improved voltage regulation which its use ensures. I cannot agree, however, that the extraordinarily low cost of 0·1d. per kilowatt-hour is the correct charge for the energy put into the battery. Mr. Taylor has assumed the most ideal conditions, and is evidently basing his estimates on the fact that the battery charge is done without running any additional plant, but merely by improving the running plant load factor. There is, however, a limit to this, and it will sometimes be found necessary to run additional plant in order that the battery may be charged in the time allocated, in which case the cost of the energy would certainly exceed the figure he gives. The figure (0·1d. per kilowatt-hour) is not one which can be realised in practice, except possibly in a water-power scheme. I would like the author's opinion as to what percentage of the peak should be taken up by the batteries in the case of a combined traction, lighting, and power system like that at Birmingham; 50 per cent. seems to me too much to be seriously entertained, and I am not aware of any place where more than 10 per cent. of the peak has been taken up. With regard to Mr. Taylor's criticism of the positions selected by the various power companies as sites for their proposed stations, it ought to be borne in mind that, although the geometrical centre of the county might be an ideal position for a central generating station, there are numerous difficulties which, in many cases, prevent this from being carried out in practice. Mr Kemp.

Mr. F. FORREST: The author's figure of 270 volts per mile seems unduly low in view of the success with which large transmission schemes operate at double this pressure. The current density he mentions—viz., 250 amperes per square inch—whilst being probably the economical limit for long lines, should certainly be greatly increased for short-branch networks if saving in capital cost is the chief object in view. The author makes a great point of the extra reliability attending the use of the batteries in sub-stations, and states that one line with batteries is as safe as double lines without them. I think it would hardly be wise to rely on the batteries, because in the event of a serious breakdown of the supply they would only be capable of taking the whole of the load for two or three hours; whereas, in mountainous country, it might easily take two or three days to locate and repair a fault in a 150-mile line. The author also states that, with batteries, it would be possible to lay the lines dead at certain times for repairs. If Fig. 4 shows an ideal load curve from Mr. Taylor's point of view, then it would be necessary to run machines night and day to charge the batteries or to run a share of the load. And when would the repairs be carried out? The author makes light of the question of the efficiency of his alternating-current battery sub-station; but engineers will hesitate to adopt any scheme which would undoubtedly involve the loss of 45 per cent. of all units they generated. Mr. Forrest.

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Mr. Groves.

Mr. W. E. GROVES: I agree with the last speaker that a single line with a battery at the far end would be impracticable. The time taken to locate and repair a fault on the line cannot be predetermined, and unless the battery is of abnormal dimensions it will be no security against a shut-down. Batteries can only be used for saving copper within very definite limits, the minimum provision being mains in duplicate, each one capable of taking full load without damage to the cable or serious injury to the reputation of the supply authority should one main fail and the battery become exhausted. A shut-down due to accident to plant can usually be avoided by the installation of a battery, but the situation where a main fails is entirely different. In stating the case for batteries, therefore, we should not bring forward saving in copper in the line as an argument in their favour, though credit must be given for their useful qualities in respect of regulation, improvement of load factor, and reliability.

Mr. Boulton.

Mr. P. R. BOULTON: The cost of energy put into the battery even in a fairly large station must be nearer 0·2d. than 0·1d., the amount stated on page 438. A previous speaker has criticised the figure taken for current density, and has mentioned a much higher figure. It was, however, the voltage drop that was the determining factor, and not the heating limit. I think it might be possible, in connection with the author's scheme, to strike a compromise and employ batteries of a smaller capacity, thus reducing the losses incidental to their use, while at the same time obtaining the advantage of better regulation on peak loads.

Mr. Rosher.

Mr. N. B. ROSHER: Referring to page 424, I should like to know how the author arrives at his figure of 25 per cent. for interest, sinking fund, maintenance, and depreciation on the copper part of the transmission line. Assuming interest to be at the rate of 5 per cent. and depreciation and sinking fund 8 per cent., this will leave 12 per cent. maintenance, an extremely high figure, especially in view of the fact that the copper part of the line only is included and not the supports. Taking the author's figures of £20 per kilowatt as the cost of copper on a 10,000-k.w. 100-mile transmission line, the maintenance at 12 per cent. works out £2,400 per mile. I would also point out that the improvement obtained by the use of a battery to supply 50 per cent. of the peak load as shown in Fig. 4 would, when expressed in percentages, mean an improvement of at least 40 per cent. in the load factor.

Dr. Kapp.

Dr. G. KAPP: The idea of using batteries to extend the radius of transmission has already been applied, though perhaps not in the extensive and perfect manner advocated by the author. Many will remember that even in some of the earliest electric railways batteries were put into sub-stations placed about one-third from the end of the line, the object being to equalise the load on the generating plant and reduce the cost of the feeders. Table A on page 428 does not seem to bear out the author's contention that a low fall water power is necessarily costly. The highest cost in this table is given for the Kubel plant, but there the fall is very great, in fact so great that Pelton wheels had to be installed.

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Dr. Kapp.

The reason why some of the Swiss water-power stations are costly lies in the fact that in many cases a steam reserve has to be provided. The power being derived from glacier streams is greater in summer than in winter, so that just when most power for lighting is wanted the streams carry least water, and the provision of a steam reserve becomes a necessity. I agree with Mr. Addenbrooke that engineers have not overlooked the possibility of using the accumulator as a means of extending the area of the district served, but they naturally shirk the financial responsibility. I might mention a case in point where the use of accumulators has been fully considered and then abandoned. This was in the remodelling of the public supply of the town of Lucerne. Originally Lucerne was served on the single-phase system by two stations—one water, the other steam power. Then the town acquired a large water power in Engelberg, and this was transmitted to Lucerne and distributed by means of the old network, which was perfectly serviceable. But the question had to be faced as to what would happen if the transmission line were interrupted. To provide against this, two methods of accumulating energy were discussed, one by batteries and the other by the creation of an artificial reservoir on a neighbouring mountain into which water would be pumped when there was a surplus of power. The hydraulic storage scheme appeared to the engineers rather the safer of the two, and in planning the sub-station the possibility that at some future time such a system of storage might have to be adopted was kept in view. It was not a new departure; there existed already at that time in Switzerland one installation where the principle of storing energy in an artificial high-level reservoir had been put into practice. This is in Canton Aargau, and the work was carried out by Messrs. Brown-Boveri. The efficiency can naturally not be very high, about 50 per cent. or thereabouts, but as the energy required to pump up the water is surplus energy costing practically nothing, and the maintenance cost of the hydraulic works is very small, there is a clear gain by this kind of storage. I might mention that in connection with the large power station now being erected by the town of Bale on the Rhine at Augst, provision is being made for hydraulic storage, if at a future time it should be required, the site for the future reservoir being on a high plateau on the right bank of the river.

Mr. Addenbrooke.

Mr. G. L. ADDENBROOKE (*communicated*): The main object of the paper, I take it, is to show that by the use of accumulators at the distributing end of feeders the copper section in them might be reduced or their length correspondingly increased. To avoid getting involved in a mass of figures, I think I shall do best to relate my own experience in the matter. In my paper on "High-Voltage Lamps and their Influence on Central Station Practice,"* written before the great extensions in distribution at 400 to 500 volts had taken place, very full data as to the cost of feeders were given. Considerable space was devoted to this method of using accumulators, very closely on the lines Mr. Taylor is now advocating, and I think he will find, if he will look

* *Journal of the Institution of Electrical Engineers*, vol. 25, p. 208, 1896.

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Mr. Addenbrooke.

the paper up, that very much the same arguments were used in their favour, together with similar estimates of their costs. I see that at that time, just thirteen years ago, the cost of accumulators was put down as £13 for the battery alone, as compared with the £10 Mr. Taylor gives in his paper. Other costs for accessories, including buildings, brought up the capital cost to £19 per kilowatt as against £13 10s. in Mr. Taylor's estimate, although this does not appear to include buildings. Against this, in my paper the sum of £19 per kilowatt was taken as the cost of large central-station plant, whereas the cost at present would be about £13. Relatively, therefore, the position does not seem to have altered very much. On looking back over the practice of the last thirteen years, while the practice which I advocated as regards feeders has been largely adopted, several well-known central station engineers have from time to time also assured me that my figures were closely borne out in practice. On the other hand, it does not appear that the suggestions as to the use of accumulators on the ends of feeders have found general favour, not because the matter has been overlooked by engineers, but because each one took up the circumstances of his own particular installation, and has found that on the whole the balance of advantages did not warrant the outlay in accumulators, and it seems to me from the prices I have mentioned above the relative position has not altered very much since then, and therefore I take it that although the argument may be difficult to put on paper, yet when one comes to take specific projects, there are valid arguments sufficient to outweigh the apparent advantages which the use of accumulators would give. An economical and cheap method of storage has, of course, been always the ideal of the central station engineer, and I do not want to damp Mr. Taylor's ardour in the matter or to deprecate the very careful study of the question. There are cases, such as in the centres of large cities and where tramways have to be supplied, where the use of accumulators in the way suggested by Mr. Taylor is justifiable, and has been applied, and any improvements in accumulators or reduction in their capital cost would lead to extension of such applications. For instance, it has occurred to me that a very large power company or corporation supplying such a large amount of energy as we may contemplate in the future, might find that it paid them to run an accumulator factory themselves, doing their own repairs and making their own plates. If they could work on a sufficiently large scale they might be able to make plates at a sufficiently low figure to warrant their use on an extensive scale, but the time has hardly come when such a thing is practicable.

Coming now to the question of transmission lines overhead and underground, I think Mr. Taylor has perhaps not quite grasped the practical position. Assuming that a line of a certain capacity is erected, and the line is necessary in any case, the cost of double the section of the copper or of raising the voltage 50 per cent. is a comparatively small addition to the whole cost, and in this way the full demand can be met by supply from the central station. Again, I

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do not think it is altogether fair to base calculations on a line 100 miles long operated at 27,000 volts; from the list of transmissions given in the paper it is clear that in modern practice at least 50,000 volts would be used for this, and I think with modern forms of insulators there would be no difficulty in running lines at that voltage even in this country. Doubling the voltage increases the amount of energy conveyed with the same percentage drop about four times, and alters the basis of calculation altogether. The same argument applies in connection with underground cables; to slightly increase the section of the copper does not by any means proportionately increase the cost of the whole feeder, while with regard to the question of duplicate lines it is the object of power companies, as they extend, to work almost entirely by means of loops. There may be, from time to time, cases where the adoption of accumulators will be advantageous, as Mr. Taylor suggests, but I think we may take it that their advantages are fully understood by Continental and American engineers, and, if on the balance of arguments it had been found profitable to instal them in the manner suggested by Mr. Taylor, we should have already had more numerous examples. Mr. Addenbrooke.

Finally, I am glad to see the attention which Mr. Taylor has drawn to the work which is being done in France with overhead transmission, and particularly to the way in which, by carriage of these high-voltage lines across the country, the smaller townships and villages are able to secure the advantages of light and power. It has always been my view that there was room for work on the same lines in a considerable number of districts in this country if it could be carried out in the same way that it is being done abroad. In two or three instances I attempted to lay the foundations for such work, but much to my regret I found the legal and parliamentary obstacles so serious, and the demands of the local authorities so onerous, that I was reluctantly driven to the conclusion that until matters in these respects could be amended, there was little hope that capital could be profitably devoted to such purposes, however advantageous the results to this country. I trust that the publicity given by this paper to the methods of work in a neighbouring country may do something to draw attention to the matter, and lead to better facilities being given for enterprise in this direction.

Mr. R. Orsettich (*communicated*): The question raised by the author is of great importance in the design of power-transmission plants, and one which in the last ten years has received a large amount of attention from engineers, owing to the difficulty of ascertaining beforehand with any accuracy the probability of profit of such large installations. A great many data as to the design and cost of some up-to-date plants have been published, and are available for use as a basis of similar calculations. I will give a few figures which I have collected, partly from previous work in this direction, and partly from some friends who work still in the same field. It appears to me that my figures differ to a considerable extent from those which the author Mr. Orsettich.

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Mr Orsettich.

has taken as the basis of his views, and will therefore affect to a great extent the results arrived at.

Dealing first with the question of voltage, I think that the figure of 270 initial volts per mile is taken too low. The well-known American rule of thumb is 1,000 volts per mile for the first 3 miles and 400 volts per mile for each subsequent mile. In this way a transmission of 15 miles would require 7,800 volts, whereas only 4,000 volts would be considered necessary by the author. On a 100-mile line, instead of the 27,000 volts proposed, one would have to take 42,000 volts. If one considers that the cost of the copper is in inverse ratio to the square of the voltage the effect of the alteration would be easily seen. The figures stated can also be found in actual installations—for instance, the extension of the Vizzola Transmission in the north of Italy will work at a voltage of 45,000 for a maximum distance of 113 miles. The new plant that Messrs. Siemens have installed for the Spanish Hydro Electric Company is transmitting 16,000 H.P. (later 32,000 H.P.) 160 miles away with 66,000 volts. Further, some 12 plants in the United States, whose maximum distance is about 100 miles, are working with a voltage of 60,000 or thereabouts. The necessity of using high voltage in order to increase the range of operation is also borne out by the fact that several companies who in the beginning had put down a plant working at what was estimated at the time to be sufficiently high voltage, found out later that in order to obtain economical conditions of working they had to raise their voltage as soon as the experience gained in the working of the line enabled them to do so with safety. Examples of this are: The Electra Transmission of the Californian Gas and Electric Corporation, working in maximum of 154 miles, raised the voltage from 36,000 to 55,000; the Kander Works in Switzerland, working 28 miles, originally put down plant at 4,000 volts, which was raised later to 16,000 volts; the Beznau Works, also in Switzerland, with a distance of 29 miles, had to raise the voltage from 8,000 to 25,000.

Whilst agreeing with the author that a low voltage is safer and connected with several advantages, I think that the fact that high tension is being used to such a great extent in so many plants in different countries is sufficient proof of its practicability and reliability, and that such systems cannot be disregarded when considering from an economical point of view plants of the magnitude of 10,000 k.w. and a transmission of 100 miles. The other parts of the line affected by an alteration of the initial voltage would be the supports, the transformers, and the switchgear. The cost of the supports per mile of line are practically independent of the voltage, as the weight of the line and the cost of erection are reduced with increasing voltage, whereas the weight of the insulators increases with the voltage. Between 20,000 and 30,000 volts the cost of the supports to the line will only be increased by about 4 per cent., and between 20,000 and 40,000 by about 12 per cent. The cost of the transformers hardly varies at all between 20,000 and 30,000 volts, and about 8 per

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Mr. Orsettich.

cent. between 20,000 and 40,000 volts. The switchgear remains practically the same, the lightning arrester only causing an increase in this item of 4 to 5 per cent. for 40,000 volts, compared with their cost at 20,000 volts. As, however, all these items taken together represent only an increase of about 28 per cent. of the cost for doubling the voltage to 40,000, it will be seen that this is entirely cancelled by the saving in the cost of copper, which will now be reduced to one quarter of the original amount. In addition to the above, the heavy amount put down by the author for the cost of copper has also to be accounted for through the limit fixed for the combined drop in the line. In my opinion, assuming that one should select such a low voltage as 27,000 for a 100-mile line, the combined drop should at least be fixed at 25 to 30 per cent. instead of 13 per cent. I explain later that the cost of producing the current in hydraulic installations is a fairly indifferent item, and that when the plant has to work with steam power the losses of the line do not come into account.

Some of the figures given by the author as to the cost of the supports for the line should also, in my opinion, be revised. A number of long transmission lines executed in the last five or six years in the north of Italy, and passing through a county which could not be called very favourably situated with regard to atmospheric conditions, were executed at a remarkably low cost. I refer more particularly to the flexible metallic supports arranged at great distances (about one-tenth of a mile) from one another with great sags in the lines. This type of support has also the great advantage of enabling a duplicate line to be used whenever required without necessitating a separate set of supports. A line of this kind fitted with 14 metallic supports to the mile, each suitable for six $\frac{3}{8}$ in. diameter wires, would work out complete, including erection and insulators, but exclusive of copper, at £210 per mile. As a line of this kind must be included amongst the heavy lines, it will be seen that the cost is exceedingly low. The life of the metallic poles can be taken at about twenty to twenty-five years, and it therefore seems to me that the figure of 25 per cent. per annum included by the author for sinking fund, depreciation, and maintenance is very much higher than what is usually assumed to be a commercial figure.

To the proposed adoption of storage batteries in connection with long-distance transmission, I am afraid most engineers will have some grave objections. The principal one would be the necessity of converting the alternating current to continuous, with its well-known handicap of rotating machinery and expensive switchgear. Further, the range of distribution from each battery would be very limited on account of the low voltage, this in its turn requiring very expensive feeders and heavy drop, which will come in addition to the losses of transformation in the machines and in the battery. The limited range of each battery would involve the necessity of using a very large number of batteries. It is well known that the area of distribution is a very large one for most of the existing transmission lines, as is shown by the

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Mr. Orsettich.

fact that many times the distribution itself is done at 2,000 to 3,000 volts. The argument of the author that the use of batteries will not necessitate a second line of transmission because of the increased safety does not appear to me to hold good, as the battery would be only designed to supply the peak load, and therefore in the best cases to keep up the supply for half a day in case of breakdown. The peak itself is not of real importance as far as the line is concerned in an installation of this kind, because there is always a large amount of reserve in the generating station which can be used to overcome the drop of the line at the moment of maximum demand.

The real difficulty with hydraulic plants lies in the fact that the supply can be kept up only for nine or ten months at the most, and that a reserve in steam plant is necessary for the other two months. This steam reserve is always placed in the centre of the area of distribution, and the cost of the line therefrom affects in an entirely different way the current produced under these circumstances. Whether under these circumstances it is advisable to use one or more storage batteries seems to me a very difficult question to answer, and most probably will have to be decided on the merits of each individual case.

Mr. Taylor.

Mr. A. M. TAYLOR (*in reply*): I will deal with the speakers as far as possible in the order of their communications.

Replying to Mr. Chappell, I would say that the cost of running lines in this country dealing with heavy powers would probably be much greater than in the United States, as the Post Office would probably take exception to large amounts of power in a single circuit; and to run several circuits or one line of towers would be as costly as my estimate indicated. With regard to the five systems alluded to in the United States, I am not satisfied that these are operating under the conditions postulated in my Fig. 4, my recollection being that the only systems so operating are those in which batteries are used as "buffer batteries," to absorb the momentary variations in power. It would be interesting to hear the views of the firms who put down these installations as to whether they are successful or not; and, if unsuccessful, to know why they failed. In reply to Mr. Kemp, it is quite true that my estimate of the minimum cost of current is based on the conditions stated by him; but, on the other hand, the mere running of the same amount of plant for longer hours would sufficiently extend the limit to which he alludes to enable the additional load of about 50 per cent. contemplated for a steam station to be taken up by the battery, the total kilowatt capacity of plant now run not being in this case exceeded, and under these conditions the cost would be very little in excess of that estimated for the most favourable conditions. In mentioning an *addition* to the existing station load of 50 per cent., to be taken up by the cells, it will be understood that this is the same thing as stating that it would pay to take up 33 per cent. of the *existing* station load by the cells.

In reply to Mr. Forrest, I think it must be agreed that if the supply were, for example, being distributed over a large town, it would be

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Mr. Taylor.

very much better, in the case of a breakdown in the long-distance line, to have two or three hours in which to notify consumers of the impending stoppage, than to spring it upon them unawares. It may be mentioned that, as regards the breaking of an overhead line, complete immunity from interruption of supply could not be secured (where there was no storage) by having two circuits, unless these were carried on two separate lines of towers, at such a distance apart as to secure absolute safety from the back lash of a breaking wire. As regards the deadening of the line at certain times of the day for repairs, I would point out that there is a day and a half at the end of every week available for charge, of which I have not taken account in my Fig. 4. As regards the efficiency of the accumulator sub-station, Mr. Forrest is no doubt aware that my proposals would not involve any greater percentage of losses in line or plant at the time of peak load than obtains under the ordinary methods not employing batteries. The extra units required to compensate for losses in batteries and in charging plant are merely made up for by running the generating plant for longer periods than it would otherwise be run. Mr. Forrest's statement would convey an impression as to inefficiency which is really not the case. In reply to Mr. Groves, the battery which I am proposing would be of quite abnormal dimensions, and would be capable of taking the whole output of the system for short periods without injury. I do not think it would pay any supply authority to have 100 per cent. of its copper standing idle, which is what I understand Mr. Groves to suggest. He is probably speaking from the point of view of distribution in a large town, which is somewhat different from the case of distribution by power companies. I do not advocate the battery as a standby against broken-down underground mains, except under special circumstances.

In reply to Mr. Boulton, I cannot agree that the cost of energy put into the battery is nearer to 0·2d. per unit than 0·1d. I should be prepared to admit that in certain cases it was nearer to 0·15d. than to 0·1d. As regards the other point raised, the losses incidental to the use of batteries are not, on a water-power scheme, at all so serious as Mr. Boulton and one or two speakers seem to imagine. In any case no larger plant is required at the sending end. In reply to Mr. Rosher, the figure of 25 per cent. has, I agree, been taken too high, and 20 per cent. is probably nearer the mark. My figure was, however, intended to cover not only the copper, but the cost of insulators, towers, etc., and I added something to cover cost of way leaves, which may sometimes be a heavy item.

Dr. Kapp's remarks as regards the Kubel water-power plant are very interesting; but the data in Table A of page 428 of my paper were given as alluding to falls in which the heads were only of a few feet in amount, and I cannot help thinking that perhaps there are two separate installations of water power at the Kubel works, and that Dr. Kapp is alluding to the one and I to the other. His remarks on the storage of water are also very interesting, and in cases where sufficient water is to be found at the receiving end of the line, and where a

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Mr. Taylor. natural receptacle can be found at a suitable level, the method he advocates is no doubt superior to electrical storage. Mr. Addenbrooke's and Mr. Orsettich's remarks I have already dealt with somewhat fully in letters to the technical press, and do not propose to deal with them further here.* In conclusion, I greatly regret that I cannot, through pressure of other work, take up here the question of the saving in fixed charges introduced by the use of storage; but I shall hope to deal separately with the subject later on.

* *Electrical Engineering*, vol. 5, p. 282, 1909. *Electrician*, vol. 62, pp. 929–931 and 975, 1909.

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MANCHESTER LOCAL SECTION.

ELECTRIC TRACTION VAGABOND CURRENTS.

By J. G. CUNLIFFE, M.Sc. Tech., and R. G. CUNLIFFE, M.Sc. Tech., Students.

(*Paper received from the* MANCHESTER LOCAL SECTION, *October* 21, 1908, *and read at Manchester, March* 23, 1909.)

I. INTRODUCTION.

Owing to continuous contact of the rails with the earth, the conductivity of the track circuit is increased, whereby the electrical losses are reduced, but the resulting vagabond currents must be kept within reasonable limits by reason of the following effects, viz. :—

(*a*) Magnetic disturbance.
(*b*) Electrolytic corrosion of underground metallic structures.

Of these effects, the former was treated in a paper read before the Institution in 1902, by E. B. Wedmore, on "Earth Currents derived from Return Circuits."*

The present paper is the outcome of an experimental investigation of the principal vagabond current phenomena, and, whilst incidentally throwing a little further light upon the magnetic effects, has been chiefly directed to the elucidation of the reasons for the non-fulfilment of the early predictions of electrolytic destruction, to the possibility of such damage being encountered, and to the precautions thereby rendered necessary.

II. THE EARTH AS A CONDUCTOR.

Nature of Earth Conductivity.—At the inception of electric traction it was thought that the earth, owing to its huge bulk, could offer no resistance to the flow of heavy currents, but this was soon found to be a fallacy.

The imperfect rail bonding resulting from this belief caused a large proportion of the current to flow in the earth, with the result that, other conditions being favourable, damage from electrolysis was observed which immediately produced the impression that the conductivity of the soil was of an electrolytic nature.

In 1900 Claude read a paper before the Electrical Congress at the

* *Journal of the Institution of Electrical Engineers*, vol. 31, p. 576, 1902.

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Paris Exhibition,* in which he claimed a mixed conductivity, declaring an earth path to be equivalent to an electrolytic cell shunted by means of a metallic conductor.

At potentials below that of polarisation the current would flow only through the metallic component, and only at higher potentials could electrolysis begin.

The experiments upon which these theories were based were carried out upon gas and water pipes and rails *in situ*.

From an external source current was passed between the pipes and the rails and was found to be almost strictly proportional to the applied potential, the effects of polarisation being negligible.

Claude's theories were disputed by Larsen,† who experimented with pipes of various lengths and the same diameter, each placed at the centre of a hollow cylinder of iron, the intervening space being filled with soil taken from the neighbourhood of a water pipe.

The soil was found to form a perfect electrolyte, the amount of corrosion per ampere-hour being independent of :—

1. Current density.
2. Potential applied.
3. Kind of iron.
4. Quantity of NaCl added ; as the full theoretical amount of electrolysis was encountered in any case.
5. Frequency and duration of interruption of the current, provided there was no change in direction.

Further, it was found that, within the range of the experiment (0–20 volts), the counter E.M.F. of polarisation was almost directly proportional to the applied potential, being about 11 per cent. of this value.

These results only prove the possibility of earth conductivity being wholly electrolytic ; they do not disprove Claude's theories, as he carefully stated that the proportionality existing between the two resistance components varied with the composition and wetness of the soil, and the particular kind of soil used by Larsen may have represented an extreme case in which the metallic component was of an infinitely high value.

In our own experiments we have encountered soil which apparently showed a purely metallic resistance, the opposite extreme.

Messrs. Haber and Goldschmidt, however, in an interesting article on " Passivity of Iron," ‡ state that : " If the iron is completely passive, no corrosion will take place ; the oxygen will disperse into the soil, and, escaping notice, it has been thought that the soil had a metallic conductivity. . . . It is certain, however, that we have to deal with a paste composed of non-conducting particles and liquids which possess an electrolytic conductivity."

* *L'Eclairage Electrique*, vol. 24, p. 141, 1900.
† *Elektrotechnische Zeitschrift*, vol. 23, p. 841, 1902.
‡ *Zeitschrift für Elektrochemie*, vol. 12, p. 49, 1906

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The essential difference in the conditions obtaining for the experiments of Larsen and Claude was that in the former case the anodic and cathodic spaces were confined so that the soil would soon become saturated with the gases, whilst in the latter case these spaces were practically unlimited, allowing ample room for diffusion.

It is conceivable that the hydrogen evolved at the cathode may combine with the oxygen contained in the porous soil, which would therefore possess the properties of a depolariser; and this would greatly assist the diffusion in preventing polarisation by removal of the gases.

Without actually causing appreciable corrosion, it is possible to examine the nature of earth conductivity by the observation of secondary phenomena.

Thus the current potential curve by its upward or downward tendency indicates electrolysis and polarisation respectively, but this test in itself is insufficient, and Claude was misled by accepting its results as conclusive.

By means of the following supplementary tests the occurrences may be completely analysed, viz. :—

1. The potential gradient measured at various stages of the experiment shows exactly where the potential is lost.
2. The counter E.M.F. of polarisation may be measured at each electrode separately.
3. The actual resistance may be measured by means of the Kohlrausch bridge and compared with the apparent value.

The earth path between pipe and rail is an electrolytic cell in which the electrolyte is composed of a salt of a metal differing from that of the electrodes, and in order to determine exactly what might be expected from a purely electrolytic soil we have examined a cell composed of copper plates immersed in a strong salt solution. As general results only were required, ordinary commercial salt, being the only kind at hand, was employed, and the solution was not made up to any definite normality.

The plates were 6 in. by 6 in. and were placed 12 in. apart in a vessel 18 in. by 7 in. by 7 in. The voltage was gradually raised from 0 to 10 volts, the current density at the face of the plates varying between 0 and 48 amperes per square foot.

Readings were taken as quickly as possible, and as the majority were at the lower values of current-density, the temperature rise was only a few degrees.

The duration of the test was about 20 minutes.

Polarisation E.M.F.'s were measured by means of the calomel electrode, the syphon being placed about 2 in. behind the plates out of the stream lines. The small potential between the two solutions was neglected.

Fig. 1 shows the relationship existing between the current, the polarisation E.M.F.'s, and the applied potential.

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The upward tendency of the current curve indicates strong corrosion, which was verified by the film of oxide afterwards found upon the anode.

The potential gradients are shown in Fig. 2, and are compared with the polarisation E.M.F.'s in Fig. 3, whilst in Fig. 4 are shown the various resistance curves as constructed from the preceding results.

Evidently the resistance of the liquid falls rapidly with increasing current, owing to the solution of copper from the anode, whilst the oxygen liberated at the anode combines with the copper, producing an insulating film of gradually increasing thickness.

Polarisation is very powerful, especially at the cathode, where the

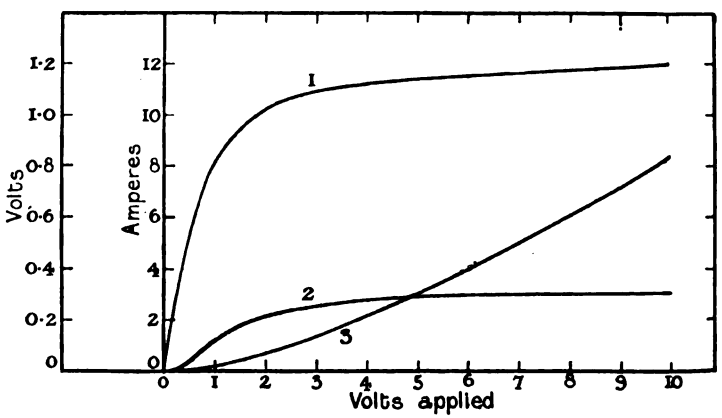

FIG. 1.—Mutual Relationships of Current and Potentials. Copper Plates 6 in. × 6 in., 12 in. apart, in a Concentrated Solution of NaCl.

Curve 1. Back E.M.F. at cathode.
" 2. Back E.M.F. at anode.
" 3. Current.

results show that the whole of the potential lost is accountable thereto. At the anode polarisation is very weak until a potential of 0·5 volts is attained, probably because the whole of the oxygen liberated up to this point combines with the copper, producing the film which has a low E.M.F. with respect to the electrolyte.

A comparison of the potential gradients shown in Figs. 2 and 2A shows the extent to which metal from the anode is dissolved in the solution, the gradients becoming more and more like those obtained with a solution of a salt of the same metal as the current increases in strength.

The experiment was then repeated with a bath of light sandy soil in place of the salt solution, with the result that the current was found to be strictly proportional to the applied potential and no trace of electrolysis was found at either electrode. The potential gradient

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was a perfectly straight line, and the resistance, as measured by the alternating-current method, was exactly the same as that given by the ratio of the potential and current.

On removing the plates, however, a thin film of oxide was found on the anode, which would account for the absence of polarisation there, and such absence at the cathode could only be explained by depolarisation, as however rapidly the gases diffused they would remain in the

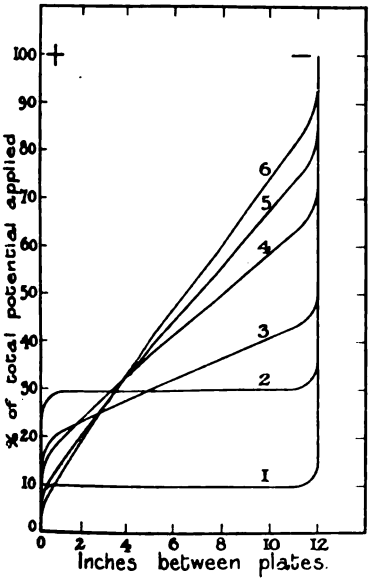

FIG. 2.—Potential Gradients. Copper Plates 6 in. × 6 in. × 12 in. apart, in a Concentrated Solution of NaCl.

Curve 1. ½ Volt between plates.
" 2. 1 " " "
" 3. 2 " " "
" 4. 4 " " "
" 5. 8 " " "
" 6. 10 " " "

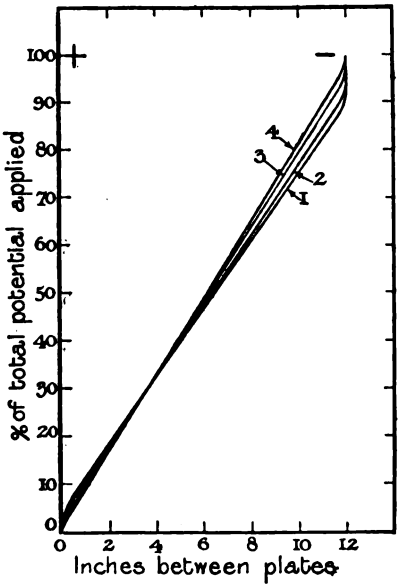

FIG. 2A.—Potential Gradients. Copper Plates 6 in. × 6 in. × 12 in. apart, in a Concentrated Solution of $CuSO_4$.

Curve 1. ½ volt between plates.
" 2. 2 " " "
" 3. 6 " " "
" 4. 10 " " "

vicinity of the plates, and would be detected by means of the exploring electrodes employed to obtain the potential gradient (see Appendix).

The specific resistance of the soil was 630 ohms per yard cube, which is very high, so that the current strength and the volume of gases produced would be very low.

In order to increase the current strength the soil was compressed and higher potentials were employed.

The specific resistance was reduced to 360 ohms per yard cube, and after being subjected to a potential difference of 500 volts for

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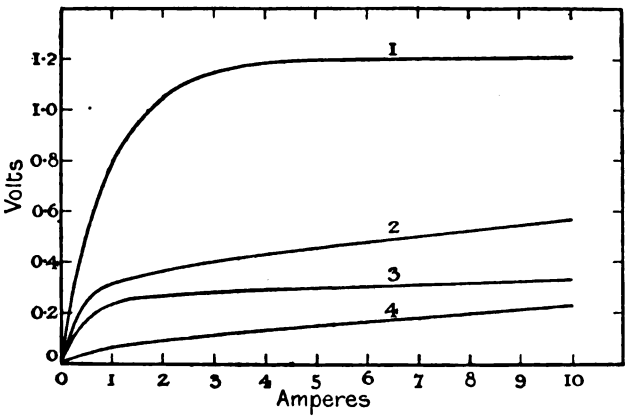

FIG. 3.—Copper Plates 6 in. × 6 in., 12 in. apart, in a Concentrated Solution of NaCl.

Curve 1. Volts lost at cathode (all polarisation).
" 2. Volts lost at anode.
" 3. Back E.M.F. of polarisation at anode.
" 4. Volts lost in film at anode.

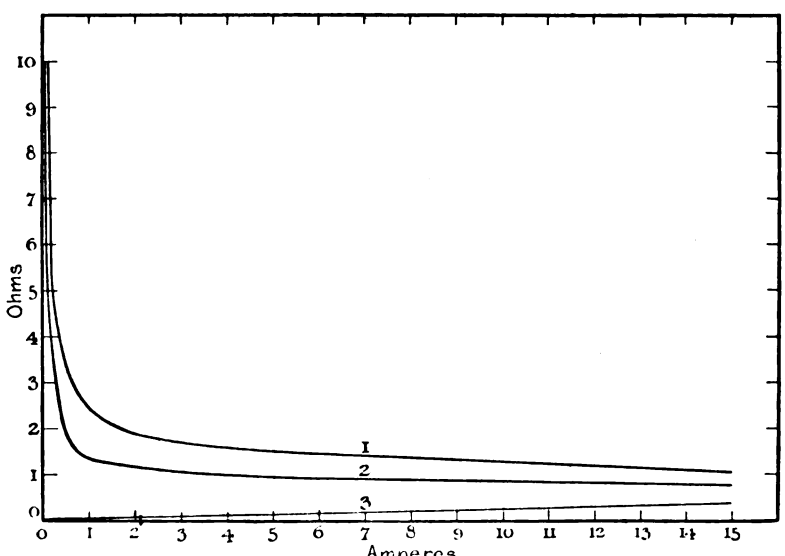

FIG. 4.—Resistance Components. Copper Plates 6 in. × 6 in., 12 in. apart, in a Concentrated Solution of NaCl.

Curve 1. Total apparent resistance.
" 2. Resistance of liquid.
" 3. Resistance of anodic film.

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several hours, a fairly strong polarisation began to appear, the anode showing considerable corrosion on removal.

Thus a soil which apparently possessed a purely metallic conductivity was found to be really of an electrolytic nature.

The experiments were repeated on a richer soil of a much higher conductivity, and an apparently metallic resistance was again observed at potentials below 10 volts, but on increasing the potential the current curve showed an upward tendency until a potential of 80 volts was reached, when it began to droop, and at 500 volts was almost horizontal. This drooping was found to be due to endosmose, the potential gradient showing the majority of the potential to be lost in the vicinity of the anode, where the soil soon began to steam.

Numerous soils have been tested, and although in many cases exhibiting an apparently metallic conductivity, have been made to show both polarisation and corrosion, and as a result we have concluded that earth conductivity is invariably of an electrolytic nature, although on account of the physical properties of the soil the fact may sometimes be concealed to superficial observation.

Factors Governing the Resistance of an Earth Path.—These are :—

Primary.

1. Length of path.
2. Area of electrodes.
3. Specific resistance of the soil.

Secondary.

1. Potential applied.
2. Polarisation and depolarisation.
3. Activity or passivity.
4. Physical properties of the soil.

The secondary factors have already been dealt with.

Fig. 5 shows the variation of resistance with distance between copper plates of various sizes buried in a vertical plane, with their upper edges lying in the surface of the ground.

The graph is that of a logarithmic function of the form—

$$R = \frac{a\,D}{b + D^n}.$$

where—

a is a function of specific resistance and size of plates.
b is a function of size of plates.
n is a function of size of plates and of distance.

Evidently the conditions are complex, and we have pursued the mathematical analysis no further, especially as, the composition of the soil being so variable, it is unwise to employ specific values for the purpose of obtaining further values by calculation.

For the same reasons we have neglected the measurement of molar

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and equivalent conductivity, measuring instead the apparent resistance between the plates, and we desire to draw attention to the shapes of the curves rather than to the values of the ordinates.

It is apparent that with increasing distance the value of the resistance increases rapidly, soon attaining a maximum, when it falls, at first quickly, then more and more slowly, finally becoming almost constant.

This may be explained by reference to the stream lines of current.

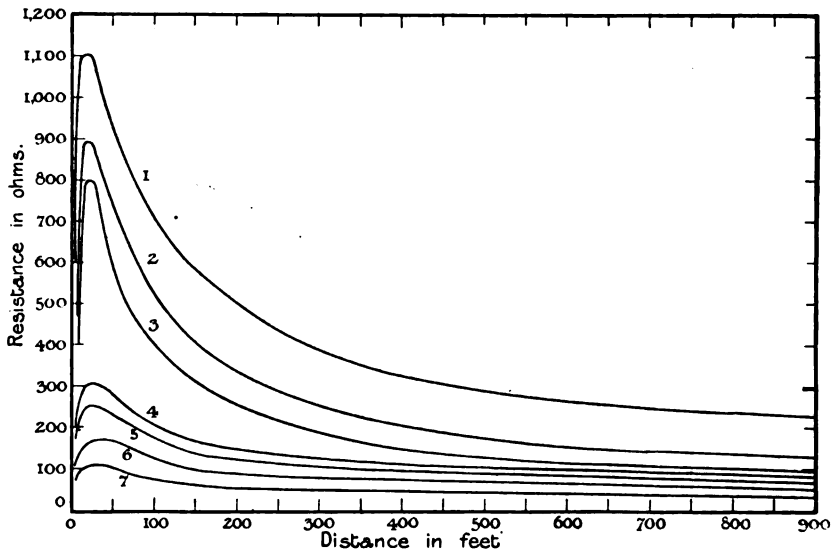

FIG. 5.—Resistance. Distance Curves. Kohlrausch Bridge Method. Alternating Current.

Curve	1.	Plates	each	0·1	sq. ft.	
,,	2.	,,	0·1	and 0·5	,,	
,,	3.	,,	0·1	,, 1·0	,,	
,,	4.	,,	0·5	,, 0·5	,,	
,,	5.	,,	0·5	,, 1·0	,,	
,,	6.	,,	1·0	,, 1·0	,,	
,,	7.	,,	1·6	,, 1·6	,,	

Thus, Fig. 6 shows the conditions with two plates very close together, when the length of the extended stream lines is seen to be considerable in comparison with the distance between the plates, and the effective area of the path is little greater than the area of the plates.

With increasing distance, however, as is shown in Fig. 7, the percentage increase in length of the extended stream lines becomes smaller and smaller, and the effective area of the path increases.

The resistance tends to rise owing to the increasing length of the path, and to fall owing to its increasing area, the balance-point being indicated by the attainment of maximum resistance.

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At greater distances the effective area increases more rapidly than the length, the rates of increase tending to equality at infinite distance, when the resistance would be zero.

It is evidently incorrect to speak of the resistance to leakage from a plate of a given size to earth, as this resistance depends entirely upon the size of the other electrode and its distance away.

The resistance falls rapidly with increasing size of plates until an area of about 6 sq. ft. is reached, when any further increase in area has little effect, as is shown in Fig. 8.

This is due to the high specific resistance of the soil, which effectually prevents the attainment of a high current density at the surface of the plates.

The resistance values given in Figs. 5 and 8 were measured by the alternating-current method, and Fig. 9, which illustrates the effects of

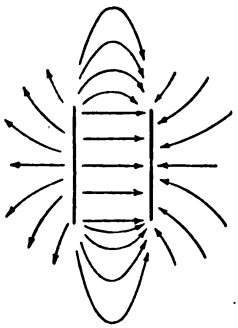

FIG. 6.—Vagabond Current Stream Lines between Earth Plates.

Plates close together.

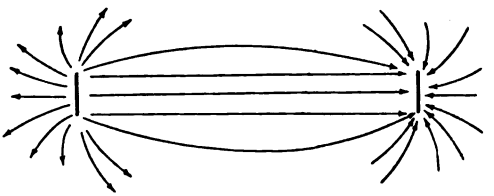

FIG. 7.—Vagabond Current Stream Lines between Earth Plates.

Plates far apart.

polarisation, shows that the shape of the curves remains unaltered when the resistance is measured by the direct-current method.

Potential Distribution and Conducting Paths in Moist Earth.—With a view to the exact determination of the conducting paths in the earth we have carried out a great number of measurements of earth potentials, this being, owing to the extremely low current density, the most satisfactory method of tracing the currents. Very soon after leaving the electrodes, however, the currents have become so diffused that even this method fails and magnetic methods have to be employed.

Fig. 10 shows two typical potential gradients between plates of equal size buried in the earth in a vertical plane with their upper edges lying in the surface.

With increasing distance between the plates the central portion of the gradient becomes more and more nearly horizontal, this being the effect of the increased area of the path already mentioned.

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The effect of inequality in size of plates is to cause a greater proportion of loss at the smaller plate than would otherwise occur, but in almost every case with equal plates the majority of the potential is lost at the cathode.

It will be observed that practically the whole of the potential is lost within a distance of 3 ft. of the two plates, and the percentage of

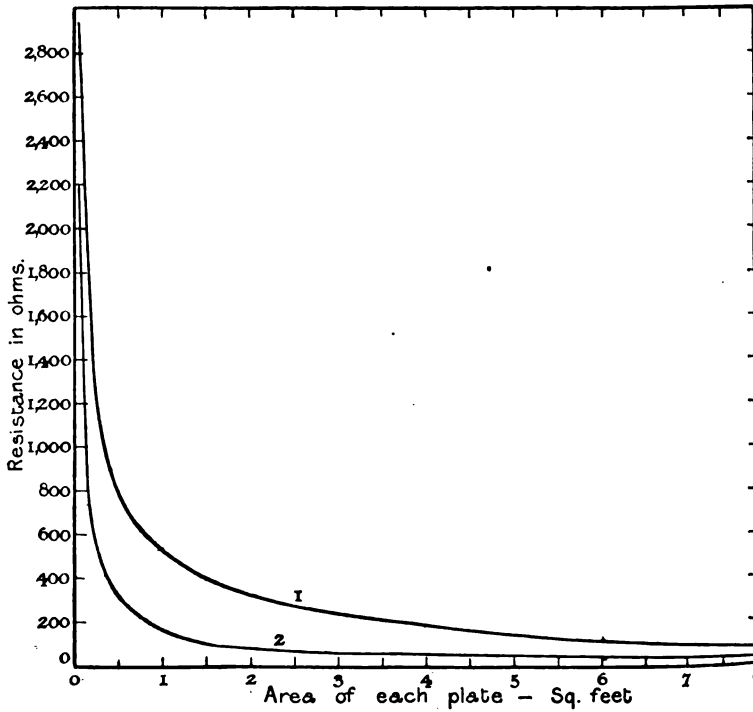

FIG. 8.—Resistance Area Curves.

1. Made-up ground containing a large proportion of pitch.
2. Ground consisting largely of iron slag and sand.

Plates 22 ft. apart.

potential lost beyond the 3 ft. becomes smaller as the distance between the plates increases.

As will appear later, this 3 ft. limit is of importance, and we have found it to be independent of size of plates, obtaining the same result from the track itself as representing the largest plates available. It is also unaffected by the nature of the soil, provided this is homogeneous over a distance of 3 ft. round the rails in every direction.

The equipotential curves, plotted to polar co-ordinates, around two

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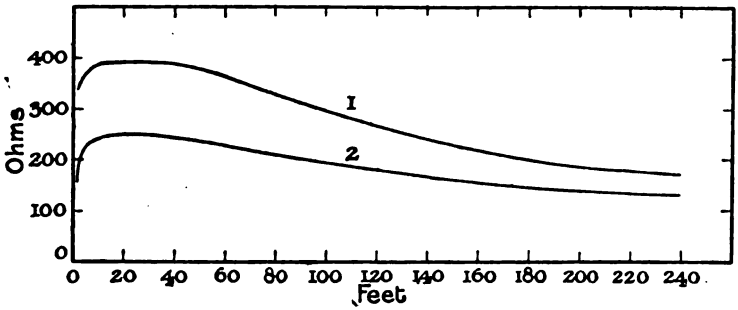

FIG. 9.—Resistance Distance Curves. Plates each 1 sq. ft in Area.

Curve 1. Resistance by direct current.
" 2. Resistance by alternating current.

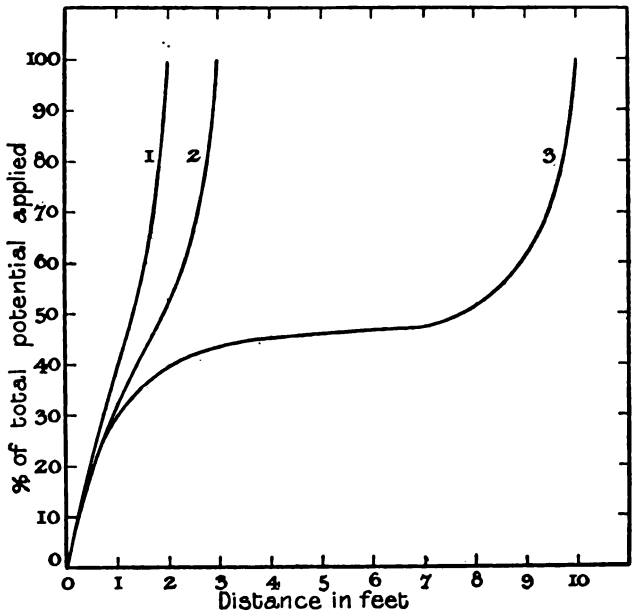

FIG. 10.—Potential Gradients between Earth Plates.

Curve 1. Plates of equal area, 2 ft. apart.
" 2. " " 3 "
" 3. " " 10 "

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spherical electrodes, are shown in Fig. 11. These are evidently eccentric circles having their centres in the axis passing through the centres *a* and *b* of the two spheres, whilst the stream lines of current, being perpendicular to the equipotential curves, may be represented by arcs

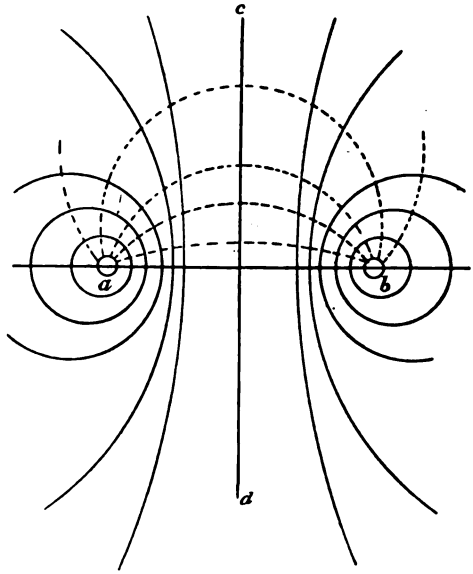

FIG. 11.—Equipotential Curves and Vagabond Current Stream Lines between Spherical Electrodes embedded in the Earth.

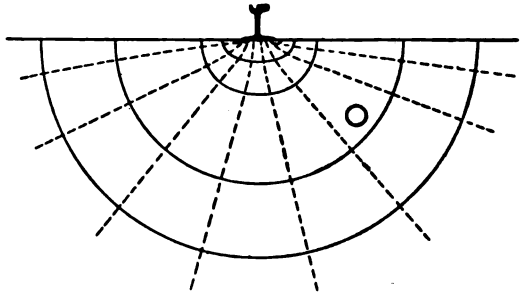

FIG. 12.—Equipotential Curves and Vagabond Current Stream Lines.
Pipe not connected to the rail.

of circles having their centres on the potential curve *c*, *d* perpendicular to the axis *a*, *b*, and passing through both *a* and *b*.

Kirchhoff* proved mathematically that the curves must have these shapes, and Quincke† verified this by tracing them in a sheet of metal.

* *Pogg. Annalen der Physik*, vol. 67, p. 344, 1846. † Ibid., vol. 97, p. 382, 1856.

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By measurements carried out in several planes we have found the equipotential surfaces to be surfaces of revolution of the curves about the axis *a*, *b*, the same operation giving the total current path.

In Fig. 12 are shown the equipotential curves and current stream lines around a tram rail. These are evidently unaffected by the presence of the pipe at a distance of 10 ft., but on connecting the opposite end of the pipe to the rail the stream lines changed to the shapes shown in Fig. 13, showing that the current was leaving the pipe.

Similar experiments carried out upon rails having pipes at various distances away show that no appreciable current enters the pipe even at a distance of 1 ft., provided there is no connection between the pipe

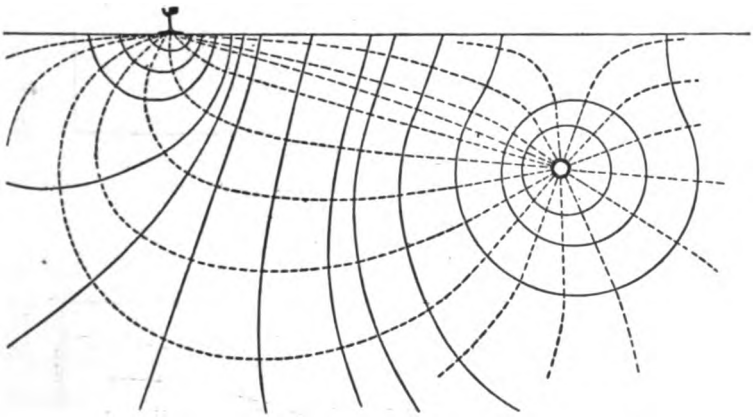

FIG. 13.—Equipotential Curves and Vagabond Current Stream Lines at the Negative Feed-point.

Pipe connected to the rail at the other end of the section.

and the rail, although at smaller distances the equipotential curves become concentric with the pipe indicating flow of current thereto.

III. VAGABOND CURRENTS.

An electric tramway track has its current taken away at intervals by means of negative feeders, and if the arrangements are properly designed, the current in the rails will flow towards the nearest negative feeder so that, midway between two negative feed-points, there should be no current flowing in the rail if the loading is uniform.

The actual conditions of loading are far too complex to admit of close study, but by assuming ideal conditions a useful knowledge of vagabond current distribution can be obtained.

There are two extreme cases to be considered, viz. :—

1. Concentrated load, represented by a single car.
2. Distributed load, represented by a very heavy service of cars uniformly spaced.

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In the former case the ideal conditions at any instant are illustrated by Fig. 14.

The so-called "danger zone" extends from the negative feed-point x to the neutral-point o, which changes its position as the car moves,

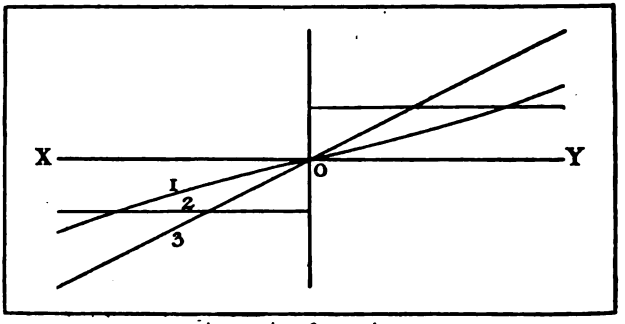

FIG. 14.—Theoretical Leakage Characteristics. Concentrated Load.

Curve 1. Current.
" 2. Resistance.
" 3. Volts.

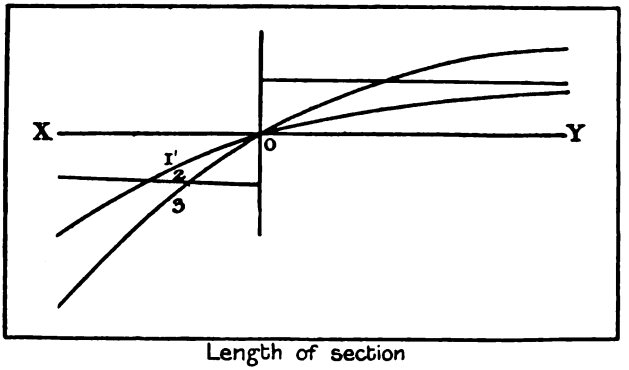

FIG. 15.—Theoretical Leakage Characteristics. Distributed Load.

Curve 1. Current.
" 2. Resistance.
" 3. Volts.

always remaining midway between the car and the negative feed-point.

At any point situated within the half of the section containing the negative feed-point, therefore, the polarisation will be alternately anodic and cathodic according to the position of the car, and the rail potential at any point can be represented by a straight line, the value varying with the distance from the negative feed-point.

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With a perfectly distributed load the curve of rail potential would be a parabola as shown in Fig. 15.

The neutral-point *o* would be fixed in position at a distance from the negative feed-point equal to 0·42 times the length of the section.

In practice, however, owing to unequal loading, the neutral-point travels in an erratic manner over a considerable length of track, so that there is again a certain range within which the rails and pipes are alternately positive and negative to each other, and there is also a range within which the pipes are continuously positive with respect to the track that is a permanent danger zone.

Fig. 16 shows the current actually flowing in the rails of a double

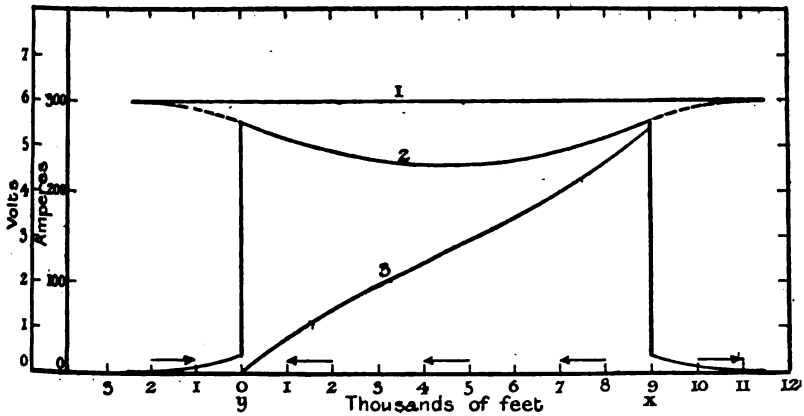

FIG. 16.—Current and Potential Distribution in Uninsulated Return.

Curve 1. Total current.
" 2. Actual current in rail.
" 3. Volts drop.

track, with a current of 300 amperes entering at a distance of 9,000 ft. from the negative feed-point.

The distribution of the vagabond current is shown in Fig. 17, the values being given per foot run of double track, equivalent to 2·3 sq. ft. of rail base pressing on the concrete, and about 6 sq. ft. of flange, etc., against the pavement.

Such heavy leakage currents are not a normal occurrence in Manchester, as four sections had to be connected in series in order to obtain them, and the rail drop was 5·4 volts, whereas the maximum value obtained in normal working is 2·0 volts, but on many other tramway systems the rail drop exceeds 5·4 volts, and the leakage currents must be extremely heavy.

Fig. 18 gives the relationship between rail drop and vagabond current, and Fig. 19 shows the effect of length of section.

Claude * found 12 to 15 per cent. of the total current to be vagabond

* *L'Eclairage Electrique*, vol 24, p. 141, 1900.

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on complicated networks, and 25 to 30 per cent. on long lines, whilst Parshall * found that on a line 8 miles long the vagabond current was as high as 60 per cent. of the total.

Neither Claude nor Parshall could find any appreciable current

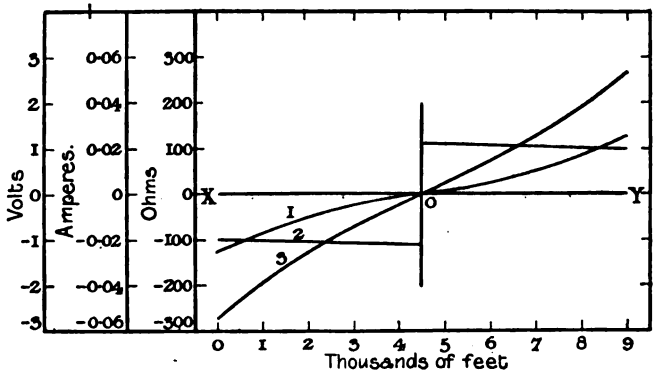

FIG. 17.—Actual Leakage Characteristics.

Curve 1. Current.
" 2. Resistance.
" 3. Volts.

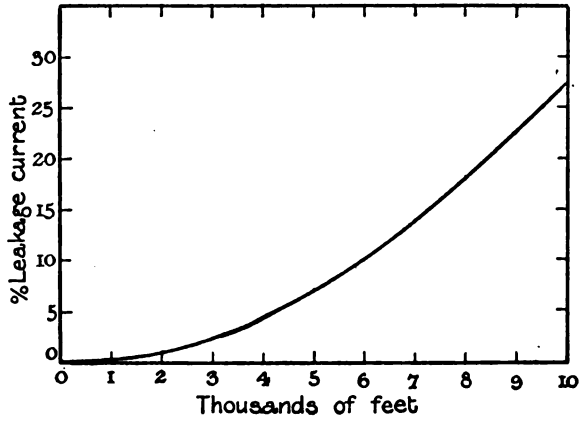

FIG. 18.—Relation between per Cent. Leakage Current and Length of Section.

flowing in the pipes, and a most careful search of the Manchester system affords no evidence of such currents.

The potential gradients given in Section II. indicate that, after overcoming the resistance due to bunching, encountered within 3 ft. of the rails, the current has become diffused over such a wide area that

* *Journal of the Institution of Electrical Engineers*, vol. 27, p. 440, 1898.

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practically no further resistance is opposed to its flow, that is, a pipe situated over 3 ft. from the rails would carry little more current than if made of earth, and the majority of pipes are at a greater distance than this.

Whatever current does, from any cause, enter the pipe must do so with a very low density, and at a distance from the point at which it leaves the rails, and must leave with a low density at a distance from the negative feed-point, owing to the lower resistance of a long return path than of a short one.

This all follows from considerations of the high specific resistance of the soil, and only in case of soil possessing a very high conductivity is there any danger of corrosion of the pipe; even in such a case, if the

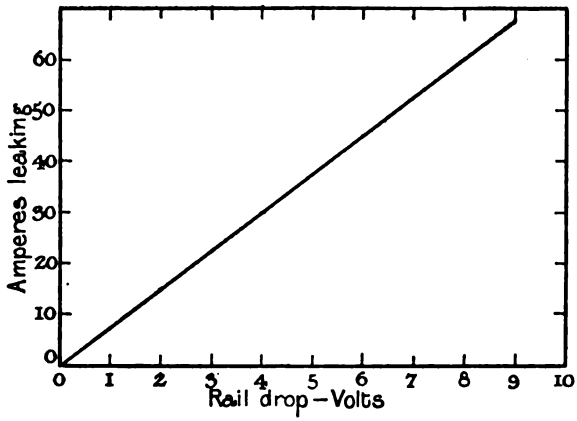

FIG. 19.—Relation between Rail Drop and Leakage Currents, with given Length of Section.

rail drop is kept sufficiently low, the resistance of the pipe itself will prevent the flow of a heavy current.

If the pipe be connected to the rail, it acts as a large earth plate, as is shown by Fig. 13, and a heavier current flows along it.

By making a temporary connection between pipe and rail at the negative feed-point, we have measured a current of 1·5 amperes flowing in the pipe, whereas no current could be measured before making the connection.

This may appear to be a low value, but the total vagabond current of the section was only 7 amperes, so that it represents 21 per cent. of the total.

On longer sections a much heavier current would be obtained.

Electrolytic Surveys.—It is still the custom of many waterworks engineers to judge the safety or danger of their pipe systems by the potential by which they are positive with respect to the rails in the danger zone.

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This is misleading, as the higher such potential, with a given rail drop, the safer are the pipes, whereas high potential is accepted as a sign of danger.

Fig. 20 shows a case in point.

In order that no current may flow in the pipe, it is essential that there should be no drop of potential along the pipe, *i.e.*, that $e_2 = 0$ (see Fig. 20).

But—

$$e_1 + e_2 + e_3 = E ;$$

therefore, for safety, we must have—

$$e_1 + e_3 = E.$$

Further, if there is no drop along it, the pipe must be throughout at the potential of normal earth, *i.e.*, at the same potential as the neutral-point o.

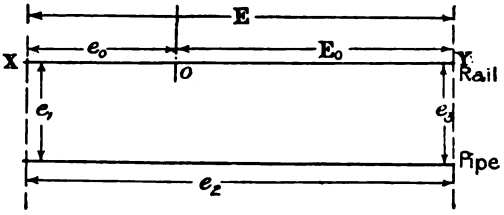

FIG. 20.—Electrolytic Survey.

Hence, the safety condition is, that—

$$e_1 = e_o,$$

and—

$$e_3 = E_o,$$

and these are the maximum possible values of e_1 and e_3.

It is impossible, therefore, to judge of the safety or danger of a pipe from a knowledge of one potential difference only; there must be three simultaneous readings, and in all cases where there is doubt, the values of E, e_1, and e_3 should be measured, with a constant current flowing, and compared.

It must be noted here that these values can only be accurately measured by means of a zero method, as the resistance of the earth component of the path is not negligible in comparison with that of a low-range voltmeter.

In this connection the capillary electrometer is very useful as a zero indicator.

IV. PROTECTION FROM ELECTROLYSIS.

Although the conductivity of the soil appears to be wholly electrolytic, and it is certain that on numerous tramway systems heavy currents are leaving the rails to enter the earth, yet, as has been shown,

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the risk of damage is very slight, and no extreme measures are required for its prevention.

The present 7-volt limit of rail drop, imposed by the Board of Trade Tramway Regulations, is the only general precaution required, and for this regulation the Board of Trade probably deserves the whole of the credit for immunity from electrolysis in this country, but it is possible that several of the remaining regulations of this Body might, with advantage, be amended.

Thus, Regulation 5 (*a*) provides that the uninsulated return shall be connected to the negative pole of the generator.

This rule is based upon American practice, and was first suggested by Mr. Pearson, the engineer of the West End Railway Company, Boston, the object being to bring the danger zone close to the station and to run copper bonds from the negative busbar to the lead sheathing of the cables.

As the latter is not the practice in this country, there is no advantage in having the rails negative, whilst, on the other hand, if the matter were left to the discretion of the engineer, he could, by making them either positive or negative, as required, shift the danger zone if necessary to avoid bad soil, so evading the only danger condition to be feared.

Again, Regulation 5 (*a*) requires the provision of two earth plates at each negative feed-point, and clause (*b*) limits the permissible resistance between these plates to 2 ohms.

These earth plates are very useful, as they enable tests to be carried out in order to obtain some idea of the conductivity of the soil in the danger zone, but, in the majority of cases, extremely large plates would be required to give such a low resistance value, and, furthermore, it would appear from our observations that the resistance between plates already installed could not be too high, and as it is to such plates that the clause now mainly applies, it might be advisable to reconsider the limit of 2 ohms.

Finally, exception may be taken to Regulation 6 (II.), which provides that no pipe shall be positive to the rail by more than 1 volt, nor negative to the rail by more than 3 volts.

As explained in Section III., it is preferable that the sum of these potentials should equal the rail drop, so that if the latter is allowed to amount to 7 volts the above limits are too low.

Despite the general safety of the lines, the utmost care should be taken at the car-sheds, as here damage from vagabond currents may easily be incurred.

The modern car-shed is a structure of concrete and steel, the rails being supported on steel stanchions sunk in the concrete floor, whilst a complex network of metal pipes is required in order to supply and take away the large quantities of water required for car-washing purposes.

The concrete is continuously wet, and any damage to piping embedded in it would be very costly to repair.

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That there is danger is shown by a case which has recently come under our notice in which a lead service pipe, which was in contact with the steel stringer girder, supporting the raised concrete floor between two bays, failed, and careful examination of the affected part showed the failure to be due to fusion by the passage of a heavy current from the rails to the pipe, the rails being positive to the pipe by 0·1 volt.

In order to safeguard the piping it is preferable that there should be a negative feed-point outside the shed, the section containing the shed being made as short as possible.

V. Conclusions.

As a result of our numerous experiments we have concluded that the general mass of the earth is at a uniform potential, and behaves like an almost perfect conductor.

This potential of normal earth can be changed locally owing to the high specific resistance of the soil. For instance, the presence of a naked current-carrying conductor may raise or lower the earth potential in its immediate vicinity, but the affected area is relatively small, and it is not conceivable to us that there can exist, between two distant points in the earth, any appreciable difference of potential provided there is no such local disturbing element within a short distance of either point.

This conception is based upon the assumption of fairly uniform earth composition, and cannot, of course, apply to an earth containing insulating strata.

For practical purposes we have fixed the limiting distance at 3 ft., to which the influence of a track, having a drop of potential below 7 volts, extends, as at this distance the potential of the soil is so little different from that of normal earth that the drop of potential along a conductor lying parallel to the rails would result in the current being so small as to be barely perceptible.

At slightly greater distances the potential gradient becomes too flat for measurement except by instruments of the utmost delicacy, and in any case at distances in excess of 3 ft. the potentials set up by the chemical action of the soil are far greater than the actual earth potentials, so that great care must be exercised in carrying out the measurements.

It can never be said with certainty that very small potentials are not due to such causes.

The above conception of earth conductivity provides an explanation of most vagabond current phenomena, and when it is further considered that the area of iron in contact with earth in a mile of double track is nearly 50,000 sq. ft., it is not surprising that vagabond current values are so high.

Owing to such magnitude of vagabond currents there is a much heavier current flowing in the trolley wires than in the rails, and it is this difference—the out-of-balance current equal in strength to the

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vagabond currents—which is responsible for magnetic disturbances experienced at a distance from the track.

If the vagabond current flowed in the ground close to the rails such disturbance would be at a minimum, and the further away the currents flow the greater is the magnetising effect.

From this consideration alone it is evident that the length of the section must be limited in cases where it is of unusual importance that the magnetic disturbance should be as small as possible, *e.g.*, in the neighbourhood of an observatory.

A consideration of Figs. 18 and 19 shows that for a given traffic density the vagabond current is proportional almost to the cube of the length of section, so that on the whole it is evident that, in order to reduce the magnetic effects, this length must be limited.

Summing up, then, it appears that :—

1. In order to reduce danger of corrosion to a minimum, it is necessary that the rail drop should be limited.
2. The limits generally imposed are still too high to afford protection against magnetic disturbances, and so special regulations fixing the maximum length of section ought to be imposed in important cases.

In conclusion, we wish to express our indebtedness to Mr. McElroy, General Manager of the Manchester Corporation Tramways, for generous facilities provided and assistance rendered in many ways.

Our warmest thanks are also due to Professor W. W. H. Gee for criticism and advice on our methods, also to Mr. Pearce, Chief Engineer, and Mr. Bolton, Sub-station Engineer, Manchester Electricity Department ; Mr. McMahon, Electrical Engineer, and Mr. Blackburn, Rolling Stock Superintendent, Manchester Tramways, and to Messrs. T. S. Greenwood, W. T. Appleton, and H. Paulsen for assistance rendered.

APPENDIX.

Methods of Measurement.

In Wedmore's paper mention was made of the measurement of earth potentials between metal rods driven into the ground.

These potentials, as has been shown, are liable to be very weak, and such methods are rendered unreliable by the chemical potentials set up between the electrodes and the electrolytes contained in the soil, which is liable to vary in composition.

Further, the accuracy of the results is affected by the counter E.M.F. of polarisation.

In order to overcome the latter difficulty, use has been made of non-polarisable electrodes composed of copper rods immersed in a saturated solution of copper sulphate contained in a glass tube, plugged with plaster of Paris mixed with the solution instead of with water.

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By using these electrodes in pairs, potentials between the copper and the solution will be neutralised, and potentials set up between the copper sulphate and the earth may be almost completely balanced by always placing the points of the electrodes on small heaps of a uniform sand dampened with distilled water.

The only unbalanced potentials remaining will be those set up between the sand and the soil, and will be very low indeed, so can be neglected in most cases.

Where these precautions are not sufficient, four electrodes may be employed, as shown in Fig. 21, but it will seldom be found necessary.

Even when all these precautions have been taken, it is never quite certain that chemical E.M.F.'s are not being measured.

Earth potentials should always be measured by a zero method, and we have found the capillary electrometer of the Ostwald type to be very useful as a zero indicator, as at low potentials it is static, and potentials as low as 10^{-3} volts can easily be detected.

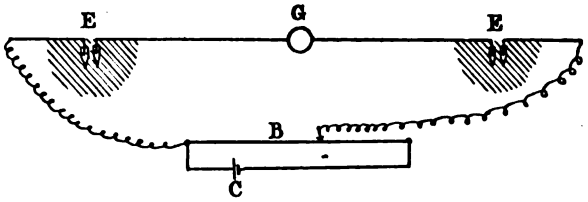

FIG. 21.—Measurement of Earth Potentials between Distant Points.

E = Electrodes.
G = Galvanometer or electrometer.
B = Bridge.
C = Standard cell.

The combination of electrometer and electrodes is perfectly dead beat, portable, and free from the influence of external magnetic fields, which are extremely powerful in the neighbourhood of tramway lines, whilst its use does not necessitate a knowledge of the potentials set up by every fresh kind of soil encountered as does that of the standard decinormal electrode.

Values of current density have been measured by means of Haber and Goldschmidt's non-polarisable voltameter, and of pipe currents by the differential method of Claude, a correction being applied to compensate for the resistance from lamp-posts, hydrants, etc., to pipes.

The magnitudes of the vagabond currents have been determined by passing a constant current through a measured length of track, and measuring at intervals the drop of potential across 50 ft. of solid rail.

The wear of the rail was obtained by means of a profile indicator, the remaining area calculated, and the resistance obtained from the known properties of the metal.

Potential measurements were also carried out at various points and the gradient plotted, actual values of the resistance to leakage per foot

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run of track being obtained by calculation from the known voltage and current gradients.

Single-electrode potentials have been measured by means of the calomel electrode, combined with the ballistic galvanometer and a condenser.

The presence of gases around the plates, referred to in Section II., has been detected by means of the combination of copper electrodes

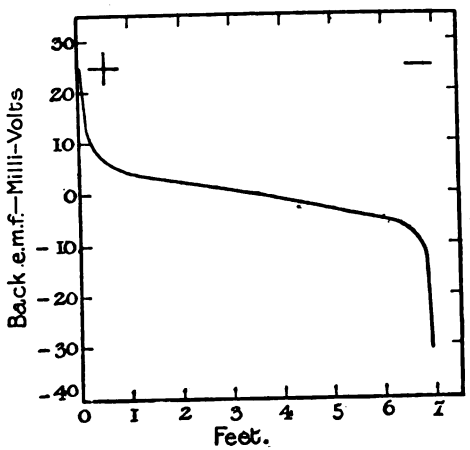

FIG. 22.—Curves of Back E.M.F. between 2 Copper Plates, each 12 in. × 6 in., placed 7 ft. apart in Sand.

Measurements taken between a fixed electrode half-way between plates and an exploring electrode moved from plate to plate. Current switched off before taking measurements.

and capillary electrometer, one electrode being placed half-way between the plates and the other being moved gradually from plate to plate, the potential being observed at each point.

The curves shown in Fig. 22 are typical of the results obtained.

Such potentials may be traced several days after the experiment.

DISCUSSION.

Mr. MILES WALKER: I think that experiments such as those illustrated in Fig. 16, carried out on a large tramway system, are very interesting. The point made by the authors in Fig. 10, which I think is the most important figure in the paper, is of course one which, from a theoretical point of view, is fairly well recognised, but which, in connection with the drop in the pipes, has been rather overlooked. As the greater part of the drop in potential occurs within 2 or 3 ft. of the rail, pipes at a distance of 3 ft. are fairly safe, but still some cases of trouble might arise. For instance, suppose a pipe laid in good conducting soil 4 ft. rom the rail, and following it for 200 or 300 yards, it is conceivable that Mr. Walker.

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Mr. Walker. the potential may be raised sufficiently high to cause a considerable current to flow along it, and this current in leaving the pipe at the joints might bring about electrolytic action. In connection with Fig. 10, it is stated that the shape of curve 3 did not depend upon the sizes of plate; but I cannot help thinking that it must do so, because, if the plates are large enough, the distance between them becomes small in proportion to their size, and then the conditions are practically those shown in curve 1, Fig. 10.

Mr. Trotter. Mr. A. P. TROTTER: The days of alternating-current traction are coming, and I should like to know a little more about the suggestion that alternating-current leakage will be larger than with continuous current, although I think it is generally admitted that alternating current is less likely to produce electrolysis.

With regard to the author's criticisms of the Board of Trade Regulations, those Regulations were drawn up by my predecessor, Major Cardew, some fifteen years ago, when there were only a few miles of tramway in the country, and that was done after a conference with the waterworks, gasworks, and tramways representatives. Nobody really knew much about it, and it was a sort of inspiration which caused Major Cardew and the conference to hit on those figures which have effectually protected the gas and water pipes in this country, and have done little harm to the tramways. The time will come when they will have to be altered. I agree with the authors that Fig. 10 is one of the most important in the paper. The subject is alluded to again on page 465. The suggestion that no electrolysis need be feared at a distance greater than 3 ft. is borne out by experience. The two most marked cases of damage that I know of occurred within 2 ft. of a rail. I have discussed this point with Mr. Hancock, the Electrical Adviser to the Government of Western Australia, and asked him for his opinion, and he said that no pipe should come within 2 ft. of the rail. This was based on experience, and is the only regulation about electrolysis that his Government has made. There are cases of corrosion, and it is my business to look after these when they occur and investigate matters. On nine occasions corroded pipes have been most solemnly brought before Parliamentary Committees. There were really only three pipes, and they each came up three times, and the Board of Trade Regulations had been exceeded in every case. If I remember rightly, there is not a single case on record in this country of a pipe being corroded where the Board of Trade Regulations have been observed and tests carried out. Generally speaking, I believe the 3-ft. rule is an excellent one. I had to investigate a case in connection with the disturbance of submarine cables by the Capetown tramways, and there I took out the fish-plates and bond in the middle of a 7-mile track, cleaned the faces, and put in an ammeter shunt. We had three or four tramcars at the far end of the line with the brakes hard down. We measured the current at the end and at the middle, and there was about 70 per cent. going through to the rail, corresponding with Mr. Parshall's figure. It is extremely interesting to hear that very careful search in Manchester affords no

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instance of damage by electrolysis due to tramways. Some four years ago a length of 18 in. of lead pipe was found to be corroded in a town near Manchester. It lay close under a tramway rail, and no Board of Trade tests had been made. I made careful inquiry, but could find nothing more than this 18 in. I asked the Water Engineer of Manchester to let me know if any case came to his knowledge, but he has not informed me of any. Mr. Trotter.

With regard to the practice of connecting the rails to the pipes, a pipe may come very close to the rail at the far end and get a good dose of current; or, on the other hand, it may come close to the negative end and the resistance may be so small that there is strong inducement for the current to leak out. I think in many cases, where there is a tendency for the current to get out of the pipe into the earth, it would be well to let it out by a metallic path with a bond, and there are scores of cases where bonding has been put in and incipient electrolysis stopped, and therefore it is not quite right to say it is not the practice in this country to make this connection. I think Fig. 20 is rather disappointing as an electrolytic survey. Such a survey is a very interesting matter. Of course, the current varies so much that you cannot get a steady reading; but a fair estimate can be made of the distribution of voltage between pipes and rails, and of the boundary between the districts in which the pipes are positive to the rails and those in which they are negative. I think it is sometimes worth while to make such a survey.

Professor W. W. HALDANE GEE: With regard to the important tests given in Messrs. Cunliffe's paper, which may be regarded as a valuable supplement to my paper of last year, I believe when I first proposed these tests there was a considerable amount of timidity in certain official quarters as to what the result would be. I assured them that I thought the whole system was perfectly safe, and the paper shows that, as far as Manchester is concerned, we need not fear damage by electrolysis. There are a number of points to which I should like to allude. The first is as to what happens when a current is passed through a saturated solution of common salt with copper electrodes. The authors say that an oxide is produced at the anode. Is there not a chloride or something of that sort produced? Was the deposit on the anode of a green or a dark colour? The test with 500 volts confirms those that I made last year, showing the importance of endosmose in causing a large resistance at the positive end, and here, with a high voltage, the effect becomes very important. Again, alluding to endosmose, the authors state that the rule for the trolley wire being positive was due to Mr. Pearson, Engineer of the West End Railway Company, Boston. In books on traction the statement is generally made that the trolley wire is positive because the insulation is much better. It dries, and we well know the positive lead always tests better than the negative in the 3-wire system. I fully agree with the authors that in some cases it might be advisable to make the trolley wire negative. Whatever is positive is likely to corrode; on the other Professor Gee.

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Professor Gee.

hand, it is also likely to dry well. It is difficult, in some cases, to reverse the polarity of the trolley wire, and I believe in Manchester it would cause considerable trouble. I am very glad the authors have made out a case for alternating leakage currents in direct-current systems. In Fig. 14 are shown the theoretical leakage characteristics in the case of a single tram on the track. There must be here a sort of alternating leakage current, sometimes making part of the pipe become positive and at other times negative, and the authors have, in Fig. 17, arrived at practical results which agree with the theory. One would like to know how Fig. 15 has been deduced. The authors show clearly that the American practice of connecting the pipes to the rails, which has been strongly recommended in many cases of bad leakage, is distinctly wrong; on the other hand, with the authority of Mr. Trotter, we may regard the "3-ft. rule" as of great importance. The measuring instruments shown on the table are no doubt novel to many here. The Kohlrausch bridge shown is an extremely handy apparatus for measuring resistances in all cases where there may possibly be electrolytes. The capillary electrometer has been despised as an impracticable instrument, but we have here an instance of engineers using a laboratory instrument restricted for many years to physiological and electrochemical work. The capillary electrometer is an extremely simple instrument, and only requires for successful use *clean* glass tubing, *clean* mercury, and *clean* electrolyte; generally one of these three is lacking, hence the difficulties experienced in using the instrument.

Mr. Smith.

Mr. C. F. SMITH: I should like to thank Messrs. Cunliffe for the paper they have given us, both on general grounds on account of its value and interest, and particularly because they are old students of ours at the School of Technology. On that account I am specially pleased to be here to hear the paper read. I notice that on page 455 the statement is made that the earth conductivity is invariably of an electrolytic nature. I suppose by that statement they do not mean that they have proved that the conductivity is exclusively of an electrolytic nature. This could only be done by quantitative measurements, which they do not appear to have made. I understand them to mean that electrolysis is always found to accompany the flow of current through the soil. On page 457 it is at first almost alarming to hear that if the earth plates are sufficiently far away from one another, the resistance between them is zero. This suggests visions of the great advantage of long distances in traction—for instance, in the case of main-line railways with a generating station in Scotland and rails connected to earth plates in Cornwall, we shall expect to find no trouble in reducing the rail drop to zero. I think what the authors should have said is that the resistance *per yard or per mile* with an infinite distance is zero. The actual resistance that they have found to exist near the electrodes due to concentration of the stream-lines is not rendered zero by an increase in distance.

In Fig. 13 the authors show an interesting diagram as to the effect

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on water pipes. It occurred to me that although they have considered the effect on pipes laid parallel with the rail, they have not said anything about the effect on a pipe which is taken across the street down which the tramway is laid. In some of the earlier tramway installations in Germany, where the gas pipes were taken from side to side of the street in order to supply various houses, it was found that there was a great deal of corrosion just at the point where those pipes passed underneath the rails. I should rather like to suggest to the authors that this would be a case where corrosion might take place, even possibly outside the 3-ft. limit, since such pipes must evidently cut several equipotential surfaces. I should like to ask the meaning of the curve of resistance in the figure on page 464, and how it is obtained; also how the exact position of the neutral point is arrived at. It is not referred to in the text. I should also like to suggest to the authors that a little more explanation as to the position of the point *o* mentioned at the top of page 463 would make their statement clearer that it is at a distance of 0·42 times the length of section from the negative feed-point. Mr. Smith.

Mr. A. MAGNALL: Being responsible for a large network of lead-covered cables in Manchester, I have on many occasions made special Mr. Magnall.

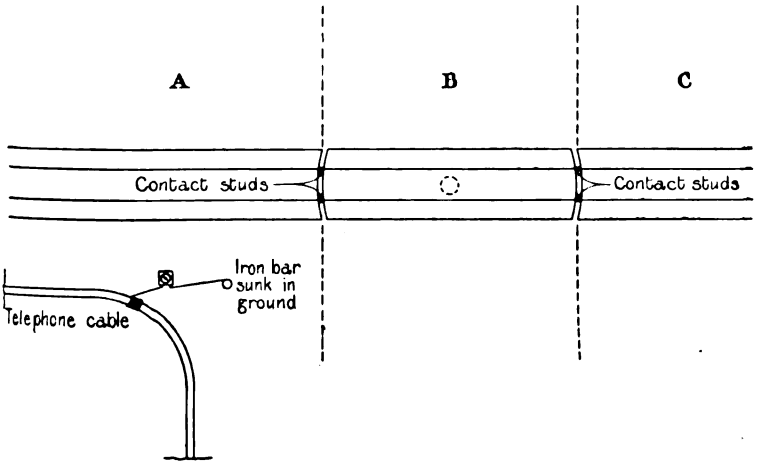

FIG. A.

efforts to try and find any signs of electrolysis, and only to-day I happened to cut out a piece of lead that has been in the streets of Manchester for the last sixteen years, and close to a very busy tramway track near the top of Portland Street, the lead being almost as good as new. I think the subject of electrolysis is one which ought not to be lost sight of, and I am quite in agreement with the remarks made last year by Professor Gee at this section. I accidently came across a case

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Mr. Magnall. of leakage the other day which may be of interest. I was in a manhole where a man was testing cable with an ordinary detector and got a current on the ordinary detector galvanometer between two cable sheaths. I tried several little experiments, and found that I was getting a current from a short length of cable. I sent up the following morning, had the voltage measured by driving a stake in the ground and then tapping on to the cable, and got a voltage of 0·2. Then the attachment was put on the cable, whilst a tramcar passed over the bridge close by, and the moment the car got on the bridge the voltage reversed, and jumped up to 2·5. When the cars were in sections A or C a potential of 0·2 volt was obtained from the earth, but immediately the car got on to the bridge or section B 2·5 volts was obtained from the cable, and the conclusion is that the return current strayed through earth, and the vagabond current distributed.

Mr. Pearce. Mr. S. L. PEARCE: It may not be generally known—but I think Mr. Trotter will bear me out—that a greater use is made in Manchester of insulated returns than in almost any other tramway system in the country. The original idea—and it is only departed from in three instances—was to lay two ½-in. feeders, a positive and a negative, to each feeding-point. That will doubtless account to a very great extent for the limited drop in voltage that has been observed in the rails, and it has also another practical advantage, which we have found to be of very great service during the past few years, that in case of a positive feeder breaking down, it is possible to make the negative feeder positive for the time being, and to work back by the rails; or alternatively it is possible to double the section of the positive feeder, making the negative into a positive, and to draw in an equivalent 1-in. cable through a pipe that may be laid in the ground, not necessarily to the same point as the other two were feeding, but very near it. That has been done in a good many cases, and it has been found of extreme value on those roads where the exigencies of the traffic requirements have called for increased section of copper.

There is only one point in the paper that I wish to touch upon, and that is the authors' suggestion on page 467 that it should be left to the discretion of the engineer to change over the return cables. Now that is a method that I think would be extremely difficult to put into operation in our own case. All our series windings are on the negative pole, all the equaliser connections in the pillars, and the switchgear connections are practically at earth potential, and I do not think it would be possible under present working conditions to change over those connections from negative to positive without inviting a breakdown at some part of the equipment.

Mr. Stewart. Mr. C. L. E. STEWART: I should like to ask the authors what would be the effect of a pipe running parallel to the track when there are a large number of service pipes crossing under the track and fairly near to it. In one instance I know of, there was a 3-in. cast-iron water main crossing underneath the track, and it probably ran alongside the track for some distance. The pipe burst about 15 to 20 yards distant, at right

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angles to the tram route, and there was a hole in it several inches across, and the rest of the pipe could have been cut with a pen-knife. Another point was as to bonding either the cable sheathing or any of the pipes to the rail when they are running parallel to the track. It seems to me if this is not done there will be potentials which are liable, if they come across anything in the ground, to produce burning of the lead, and if it is done the lead of the cables will act as return feeders. Mr. Stewart.

In the case where a pipe makes a short cut across two tramway routes, as might happen if the tramways made a circuitous route from the generating station to the centre of the town, would not the effect be rather different from that produced if the pipe ran parallel to the rail?

Mr. A. SMYTH: On page 457 the authors say, "It is evidently incorrect to speak of the resistance to leakage from a plate of a given size to earth, as this resistance depends entirely upon the size of the other electrode and its distance away." My experience shows that the resistance is also affected by the mechanical pressure on the plates, and this is a very important item in a tramway service. I also think the authors have been wise in confining their efforts in this matter to experimental work, as the conditions are far too complex for mathematical analysis. Mr. Smyth.

Mr. J. FRITH: The question of the conductivity of the soil, dealt with in the earlier part of the paper, interests me a great deal. I take it that the actual components of the soil—sand, clay, and rock—would be excellent insulators if thoroughly dry, and the conductivity of the earth depends entirely upon what these are moistened with—*i.e.*, pure water, or with a solution of various salts. The curve Fig. 5 shows clearly that theory is borne out by practice in that there is a certain distance which gives a maximum resistance between two earth plates, but I did not expect that this critical distance would be so independent of the size of the plates; for so wide a range as 0·1 to 1·6 sq. ft. the maximum resistance seems to occur at about 25 ft.; can the authors tell us what is the significance of this distance of 25 ft.? I do not think that the curves bear out the suggestion of the authors that the resistance would become zero if the distance were infinite, nor do I see any justification for the statement that there is no gain in conductivity from increasing the area of the earth plates beyond 6 sq. ft. Mr Frith.

Mr. C. J. BEAVER: To my mind, such practical conclusions as those in the paper formed on a sound basis of investigation are very valuable. Those who have studied the question of the conductivity of various kinds of soil, and the insulating properties of earthy materials, will find little difficulty in confirming the author's conclusion, that earth conductivity is of an electrolytic nature. The actual values obtained by the authors are valuable from the practical point of view to those who are responsible for the care of pipe systems and cable networks, and they have an important bearing on the vexed question of where to bond and where to refrain from bonding. They show that where pipes or cable sheaths are placed at a reasonable distance from tram rails, the currents flowing to or from them are at a density which is Mr. Beaver.

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Mr. Beaver. sufficiently low to be negligible, and, after all, current density is the factor which controls the degree of corrosion.

I cordially agree with the authors with regard to the effect of the 7-volt limit of rail drop imposed by the Board of Trade in preventing electrolytic trouble in this country. Apart from the necessity for plenty of negative feeders entailed by this 7-volt limit (of which necessity, I, as a cable maker, strongly approve), the effect of this regulation has been all in the right direction without constituting an appreciable drawback to the development of electric tramways. I had hoped that we should have heard a good deal to-night from central station engineers as to the conditions under which electrolytic corrosion of pipes and cable sheaths has been found to occur, and as to how their practical experience compares with the conclusions set forth in the paper.

With regard to the values obtained by the authors which led them to their conclusion as to the safety of the 3-ft. limit of distance between pipes or cable sheaths and tramway tracks, my own experience, which is a fairly wide one, is that most instances of electrolytic corrosion of pipes or cable sheaths by vagabond currents from tracts in this country have been due to causes which may be classified under three general headings :—

1. Where the rail drop has been in excess of the 7-volt limit due either to absence of negative feeders or to their being wrongly disposed.
2. Abnormal soil conditions where either the character or the conductivity of the soil has not been sufficiently allowed for. (Under this heading I also include wet ducts in close proximity to tram rails.)
3. Where the arrangement of pipes or lead-covered cables has been such that they afford a path of less resistance for return current than the tram rails.

With regard to this third heading, I have one or two instances in mind where lead-covered cables pass under tram tracks practically at right angles, and run to the generating station by a much shorter route than the track. In such danger zones as these electrolytic corrosion is best avoided by direct bonding, so as to provide a metallic path to convey current to the cable sheaths, which would otherwise get on by electrolytic paths, and thus set up corrosion. There are, of course, alternative methods which are obvious but usually less convenient.

Mr. Peck. Mr. J. S. Peck : Some time ago I received from America the results of an elaborate series of tests made to determine the data regarding vagabond current from single-phase railways. The amount of current returning through the earth was determined approximately by taking the difference between the trolley and rail currents, and the distribution of this current through the earth was found by stretching loops of wire along the ground in the neighbourhood of the track, and measur-

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ing the voltage induced in them by the field due to the earth currents. Some of the loops were several miles in length, and it was found that by comparing the voltage generated in loops of different size and in those placed in different positions, the current distribution could be approximated. The effect of the alternating current upon telegraph and telephone wires in the neighbourhood of the railway was also investigated. It was found that with grounded circuits it was impossible under many conditions to communicate over the wires. To overcome this difficulty, the arrangement shown in Fig. B. was devised. Mr. Peck.

An auxiliary wire is run parallel to the telegraph wire and as close to it as possible. This wire is grounded at both ends, so that in connection with the earth it constitutes a closed loop in which a voltage is induced equal to that induced in the telegraph circuit. The auxiliary wire is connected in series with the primary of a small transformer. The secondary of this transformer is in series with the telegraph circuit. Current flowing through the auxiliary wire and therefore through the primary of the transformer induces a voltage on the

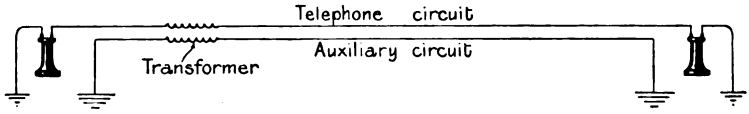

FIG. B.

secondary of the transformer opposite to and approximately equal to the voltage induced in this circuit by the alternating field. As a result, the voltage induced in the telegraph circuit by the single-phase current is neutralised. This scheme has been found to work out very satisfactorily in practice. One transformer is usually provided with several secondary coils, one being connected in series with each telegraph circuit. Mr. Trotter tells us that there has never been a single case of corrosion where the Board of Trade rules have been followed. Does this not point to the conclusion that the rules are too strict?

Mr. A. K. BENTLEY: Referring to Fig. 1, curve 2, it seems as if the values of the back E.M.F. at the anode being partly due to a film formed would increase with time as the thickness of film increased. I would like to know also how curve 3 in Fig 3 was obtained without error due to drop in film, etc. Mr. Bentley.

On looking at Figs. 11 and 12, I noticed that the lines of equal potential and the stream lines are exactly the same as those between two spheres or cylinders with equal and opposite electrostatic charges, and that they are similar to those between two equal and opposite magnet poles. It occurred to me that curves representing stream-lines of vagabond currents could be obtained by arranging on a table a few pieces of iron rod, etc., to represent rails and water pipes, placing a bar-magnet on end with one pole down on the table to represent a car and another with the opposite pole down to represent a negative feed-point. Iron filings will then give a rough idea of the

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Mr. Bentley. direction and distribution of any stray currents which might be produced.

I would also like to refer to two pieces of apparatus which should be better known to engineers. I refer to the Calomel Standard Electrode and the Capillary Electrometer.

The former consists of a glass syphon vessel containing pure mercury under a paste of calomel mixed with mercury, this in turn being covered by a solution of potassium chloride. In measuring the potential from an electrode to a point in the ground some distance from it, the end of the syphon tube is placed in the ground and the liquid forced over to make contact. After measuring the potential between the electrode and the mercury, the required potential is obtained by subtracting that between the mercury and the potassium chloride which is a standard value (0·56 volt at 18° C.). The capillary electrometer, which has been alluded to by Professor Gee, is an instrument in which the surface of some pure mercury in contact with dilute sulphuric acid is looked at through a microscope which has a fine scale in the eye-piece. A very small difference of potential between the acid and mercury will cause the meniscus to move, so that the arrangement will serve for direct measurement of small potentials or may be used as a very sensitive zero-indicator for Wheatstone bridge measurements. It is an electrometer and takes practically no current.

Mr. Watts. Mr. A. WATTS (*communicated*): On a casual glance through the paper, I notice on page 467, paragraph 7, that the Board of Trade Regulation 6 (II.) is stated to provide that "no pipe shall be positive to the rail by more than 1 volt, nor negative to the rail by more than 3 volts." I would point out that the Board of Trade Regulation does not mention these voltages. The actual reading is as follows: "That if at any time and any place a test be made by connecting a galvanometer or other current indicator to the uninsulated return and to any pipe in the vicinity, it shall always be possible to reverse the direction of any current indicated by interposing a battery of three Leclanché cells connected in series if the direction of the current is from the return to the pipe, and by interposing 1 Leclanché cell if the direction of the current is from the pipe to the return." The generally-accepted E.M.F. of a Leclanché cell is 1·5 volts, so that the figures referred to should read 1·5 and 4·5 volts respectively.

Mr. Cooper. Mr. W. R. COOPER (*communicated*): The paper appears to contain a serious error with reference to electrolytic surveys. It is well to remember that for all practical purposes the potential of a pipe in relation to the track is due to current flowing through the pipe as a shunt to the track. We cannot make arbitrary assumptions as to the potential of the pipe, and the conditions obtained from Fig. 20 are incorrect. Take the analogous case of Fig. C of two circuits B C, B D, joining at B into a common return A B (the return feeder). Let two points E F be connected by conductors E G, G H, and H F. For the moment, assume that E G and H F do not contain E.M.F.'s. Then the authors would argue that if there is to be no

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current in G H, there must be no drop in this conductor, which must be at the same potential as B, and therefore the drop in potential along E G is the same as along E B, and that along H F is the same as along B F. As a matter of fact, however, the condition for no flow is that E and F must be at the same potential, and even this is not sufficient if the conductors are placed in a conducting medium like the earth: there would then be a flow from parts of G H to parts of E B and F B near B, though this might be negligible if back E.M.F.'s resulted. The case of a pipe is complicated by the back E.M.F. of polarisation as soon as a current attempts to flow. It is much simpler to regard a pipe as a shunt to part of the track than in the way the authors have done. Thus, if T T is the track in Fig. D., and A B a pipe in shunt to it connected metallically at B, then current under the conditions shown will certainly flow from the end A to the rail if A is more than 1½ volts positive to the track, and the more highly positive it becomes (*i.e.*, the longer the shunt) the worse will be the result. If there is a pipe C D not metallically connected at either end to the track, then as soon as current tries to flow through the pipe, back E.M.F.'s E_1, E_2, appear, and unless the potential gradient is sufficiently steep to overcome these, practically no current can flow through the pipe.

Mr. Cooper.

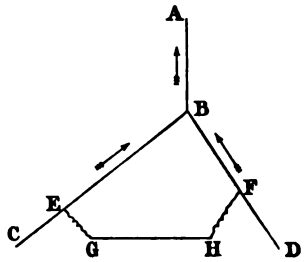

FIG. C.

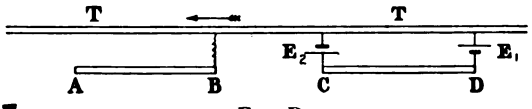

FIG. D.

Moreover, if current flows purely through the earth without taking the pipe as a path, it encounters only one back E.M.F. instead of two, and thus the pipe does not come into circuit unless it offers a real advantage. These examples are sufficient to show that it would be a serious mistake to raise the Board of Trade limits as suggested by the authors.

Mr. J. G. CUNLIFFE (*in reply*): We have stated that if the rail drop be kept low, the resistance of a pipe will prevent the flow of a heavy current along it, and Mr. Walker has pointed out that this still remains to be proved. The resistance of a pipe cannot be measured *in situ*, owing to the numerous branch paths available for the current to follow; we have had no opportunity of testing pipes which were not surrounded by earth, and are, therefore, compelled to accept published results. Larsen and Faber* state that a pipe 9 in. internal diameter and 0·5 in. thick has a resistance of 0·09 ohm per mile exclusive of

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* *Elektrotechnische Zeitschrift*, vol. 22, p. 1038, 1901.

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Mr. Cunliffe.

joint resistance, and Lubberger* is in agreement with these figures, Lubberger † also found that the water contained in the pipes did not materially affect the conductivity, and this was also observed by Meng,‡ who gives the following figures relating to the resistance of joints in pipes which have been laid for some years :—

Gas pipe joints, 0·08 to 1,200 ohms (average 230 ohms).
Water pipe joints, 0·02 to 115 ohms (average 14 ohms).

It might appear that, even with high joint resistance, the total resistance would not be very high, owing to shunting round the joints through the soil, but we have found a resistance of from 25 to 30 ohms between two 12-ft. lengths of 6-in. piping buried in the ground with their ends only $\frac{1}{8}$ in. apart, so that, on the whole, we felt justified in making the statement.

If very large square plates were used, the potential gradients given in Fig. 10, curve 3, would, especially at short distances, become similar in shape to curves Nos. 1 and 2 in the same diagram, but the surfaces encountered in practice are not square—in fact, they are strips rather than plates, and however great their area, we have found the 3-ft. rule to apply. The pipe shown in Fig. 13 is metallically connected to the rail at its distant end and the potential remarked by Mr. Walker is the rail drop.

We are gratified that Mr. Trotter has found our 3-ft. limit to be justified by experience as it is a point upon which we have received much criticism from friends who regarded it only from a theoretical standpoint. In the case of alternating-current traction systems, presumably having cars equipped with the series commutator motor, it is well known that the highly inductive series winding and the sparking at the commutator are productive of a current wave containing higher harmonics, and the impedance offered to the flow of such a current in the steel rails must be much greater than the resistance opposed to the flow of an equivalent continuous current, so that the vagabond current, other conditions being similar, must be increased. Further, the harmonics will be damped out of the current flowing in the rails, but will remain in the vagabond current wave. Of course, owing to the track construction, the resistance to leakage will be much higher, but so also will the rail drop and the length of section. There will be, owing to the high impedance, even less tendency for the vagabond currents to enter iron pipes, and even if they were to do so, the resulting corrosion would not be severe, as a long series of experiments carried out at the Manchester School of Tecohology under the supervision of Professor Gee has shown that alternating currents only cause from 2 per cent. to 3 per cent. of the corrosion obtained with an equivalent direct current. The only danger condition would be the electrolytic rectification of the alternating current.

* *Journal für Gas und Wasserversorgung*, p. 508, 1901. † Ibid., p. 723, 1901.
‡ *Elektrotechnische Zeitschrift*, vol. 22, p. 354, 1901.

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Mr. Cunliffe.

The figures exhibited by Mr. Trotter are of great interest, and are described in his contribution to the discussion on Wedmore's paper in connection with a very ingenious source and sink theorem. We agree with Mr. Trotter that there are cases where incipient electrolysis might be stopped by means of a bond, but we have shown that the bonded pipe then becomes a part of the conducting circuit, and every other pipe situated close to it is placed in danger, so that the remedy may be far worse than the disease. It would be much better to insert insulated joints in suitable positions in the threatened pipe. Such joints might consist of lengths of earthenware piping, where suitable, and would, by splitting up the pipe, keep the current flowing in any part low. In the case of tube railways care should be taken that there is no metallic connection between the rails and the tube except at the negative feed-points, where the two should be carefully bonded together, the sections of the tube being carefully bonded as at present. This would not materially endanger surrounding pipe systems, as the tube completely surrounds the track and is of very high conductivity.

After the elaborate maps to which we have become accustomed, Fig. 20 may be rather disappointing as an electrolytic survey, but it must be remembered that such surveys are in the hands of laymen, and the old form may cause unnecessary friction, and although it is undoubtedly of interest in showing the location of the danger zones, yet this can be ascertained with less labour and expense by a careful consideration of the negative feeding system and a knowledge of the load distribution, such as is always at the disposal of the traction engineer.

In the case of electrolysis of salt solution mentioned in the paper, the deposit was a dark one of oxide, but there was a greenish scum of oxy-chloride on the plate at the surface of the liquid. On several occasions we have encountered electrolysis in earth containing a large percentage of NaCl, and have invariably found the principal product to be the oxy-chloride. The following is a representative analysis of the blue-green deposit found around corroded gun-metal:—

	Per Cent.
Oxy-chloride of copper	84·89
Chloride of zinc	1·89
Chlorides of zinc and iron	2·96
Sulphate of zinc	5·63
Oxides of iron and zinc	0·83
Lime not as sulphate	0·89
Moisture and insoluble matter	2·91

Our authority for the statements concerning the positive polarity of the trolley wire is Farnham.* If the matter were to be determined by insulation only the wire would be made negative, as in any case it is very easy to obtain a very high insulation resistance, we have shown †

* *Electrician*, vol. 33, p. 16, 1894.

† Paper read September 24, 1908, at Annual Conference, Municipal Tramways Association.

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that the failure of the primary insulation is due to endosmose and would be prevented by reversal of the polarity so as to make the trolley wire negative.

We do not claim to have absolutely proved that earth conductivity is entirely electrolytic, as this could only be done by means of quantitative measurements which we have not carried out, but we have shown that cases of apparent metallic conductivity may be shown to be only electrolytic conductivity in disguise, and we have found all soils tested to be insulators when dry, and that their conductivity depends entirely upon the presence of water in which their soluble salts are dissolved. This being the case, the conductivity can only be electrolytic, and we are of opinion that the sentence quoted from Messrs. Haber and Goldschmidt in Section II. of the paper forms an accurate statement of the facts.

With regard to the statement that at infinite distance the resistance between two earth plates would be zero; this, of course, is incorrect, as there would still be the resistance near the surface of the plates, as is shown so well in Fig. 10. The curves in Fig. 5 are asymptotic not to the axis of abscissæ but to axes parallel thereto, and the word "zero" ought to read "constant." At distances in excess of 2,000 ft. the resistance is practically constant.

A pipe crossing immediately below the rails would be subject to a double corrosion:—

1. A local action due to the cutting of different equi-potential surfaces which, owing to the steep potential gradient, are close together.
2. A corrosive effect, due to any current which might happen to be flowing in the general mass of the pipe, if the crossing point happened to be in the danger zone.

We do not agree with Mr. Smith that there would be any corrosion in such a case if the pipe were outside the 3-ft. limit, as in any case the pipe is carrying no current, and in the case mentioned by Mr. Stewart, where the pipe cuts across a curve in the track, so as to cross twice, the conditions are exactly similar to those illustrated in Fig. 20 for a pipe parallel to the rail, the only possible difference being that the rail drop might be a little higher. The curves of Fig. 17 are explained on page 463, paragraph 5, but as several members have asked to have these figures explained I propose to show how Fig. 15 is deduced, the reasoning applying also to Figs. 14 and 17. Consider a track of length L subject to a uniformly distributed load, *i.e.*, the current flow increases uniformly from dividing-point to negative feed-point. Then, if i be the current flowing in a small element of track of length δl situated at a distance l from the negative feed-point, and if I be the total current flowing, it is obvious that—

$$i = I\left(1 - \frac{l}{L}\right), \quad \ldots\ldots\ldots \quad (1)$$

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and. if r be the resistance of unit length of track, it is easily shown that the track potential e at distance l is given by the equation—

$$e = I r\left(l - \frac{l^2}{2L}\right), \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

and that the total drop in the section is—

$$E = \frac{I r L}{2}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

The curve representing rail drop is evidently a parabola, and its area is—

$$A = \frac{I r L^2}{3}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Suppose now that the resistance to leakage from the rail may be represented as that due to a uniform film at the surface of the rail.

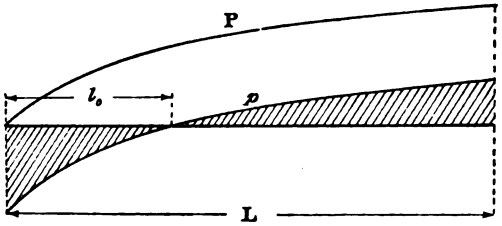

FIG. E.

Then it is obvious that the area enclosed between the parabola P and the datum line in Fig. E must represent the leakage current with a perfect earth plate connected to the track at the negative feed-point. In practice, however, there is no perfect earth plate, and current leaves the rails in the neighbourhood of the dividing point to enter again in the danger zone. Evidently the parabola may be placed in the position indicated by curve p in Fig. E, making the shaded areas equal since the current entering the rails must be equal to the current leaving. By the properties of the parabola, it follows that the length l_0, being the distance from the negative feed point to the neutral point, is given by the equation—

$$l_0 = L\left(1 - \frac{1}{\sqrt{3}}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$
$$= 0{\cdot}424\ L.$$

The total vagabond current, formerly given by equation (4), is now equal to—

$$a = \frac{1}{3\sqrt{3}} \cdot \frac{I r L^2}{3}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

By considering separately the resistance from successive small elements of rail on either side of the neutral point to the whole of the rail on the opposite side, the resistance curves shown by Figs. 14 (2) and 15 (2) are obtained by reference to Fig. 5, and curve No. 2, Fig. 17,

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Mr. Cunliffe.

being obtained directly from the current and potential gradients in the rail, verifies the forms arrived at. It is evident that the resistance curve is not exactly horizontal owing to the effect of distance, but the same method may nevertheless be employed.

The bridge referred to by Mr. Magnall is evidently the Trafford swing bridge which is crossed by our cars. In order to ensure exact alignment there is a hydraulic ram attached to the abutment, working in a cast-iron socket in the bridge. Both cylinder and socket are bonded to the rails, but there is the film of water between the ram and the cylinder walls in addition to the rubbing contact between the ram and its socket, so that the potentials measured are easily obtained on a car passing over the bridge. There is no danger to the bridge structure, as the turntable is placed on the bank of the canal. We are glad to hear from Mr. Magnall that electrolysis of lead cable, even where exposed to the vagabond currents, has not been observed in Manchester, and this has been supported by Mr. Haines, the Water Mains Superintendent, who states that corrosion of the iron pipes has not been more severe since than it was before the tramways were electrified, some nine years ago.

The methods described by Mr. Peck are interesting as they open up possibilities of direct measurement of alternating vagabond current density, such measurements in the case of direct currents being possible only in the immediate neighbourhood of the rails, owing to the very low values encountered. With regard to the designing of electrical machinery so as to work on the verge of trouble, this is where the real skill of the designer is realised; but we would remind Mr. Peck that there is a great difference between a structure and a machine, and where such huge interests are at stake, it is well to allow a large factor of safety, and the Board of Trade limit of 7 volts rail drop can be met without undue expense.

The effect of mechanical pressure on the resistance between two earth plates is to slightly lessen the resistance the greater the pressure, the resistance becoming constant at a pressure of 300 lbs. per square foot in sandy ground. The critical distance at which maximum resistance is encountered is not exactly 25 ft., but increases with increasing area of plates, as would have been apparent had the curves been plotted to a larger scale. The E.M.F. of a Leclanché cell is generally taken as 1·4 volts, but this value is not maintained throughout the life of the cell, and it would appear that the Board of Trade has considered 1·0 volt to be a reasonable value, as their regulation 5 (*b*), which formerly referred to the E.M.F. of four Leclanché cells, now specifies 4·0 volts instead, the current produced remaining the same, and this is why we have taken 1·0 volt in order to illustrate our suggestion *re* regulation 6 (II.) in Section IV. of the paper.

Mr. Cooper does not appear to have thoroughly understood our remarks relating to the electrolytic survey. Thus, we do not wish the Board of Trade to raise the potential between the rails and pipes; we merely wish them to realise that, with a fixed rail drop, the values of

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Mr. Cunliffe.

such potentials are quite beyond their control, and to alter regulation 6 (II.) so as to bring it in line with existing facts. Further, it has never been generally realised that the earth potentials observed are effects and not causes of the flow of vagabond currents, that the only electromotive force superimposed on the earth circuit is the rail drop, and that this, by its sense, determines absolutely the direction of flow of the vagabond currents, whether in pipes or earth. In stating that, in his Fig. D, if the pipes at A were at a potential higher by some 1·5 volts than that of the rail, current would flow back along the pipe from A to B to enter the rail at the bond shown, Mr. Cooper clearly betrays this misconception. We have not stated that the pipe shown in Fig. 20 forms a shunt to the whole of the rail, as will be seen by reference to the description of the vagabond current circuit on page 465, paragraph 1. During the reading of the paper this was further illustrated by Fig. F, which shows the vagabond current stream lines flowing from a small element of rail near the dividing-point. It has been the custom to refer to the short-circuiting of the soil by a pipe, but it would appear that the reverse is really the case, and that the pipe is short-circuited by the soil.

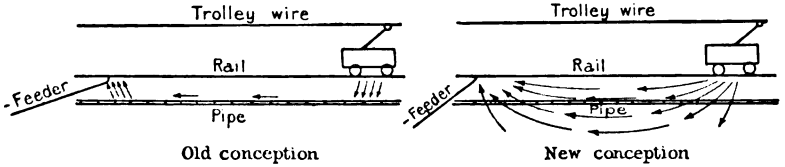

FIG. F.

The path offering minimum resistance is illustrated, and it is evident that only a small portion of the pipe is really available as a part of the return circuit for the vagabond current from each such element, so that we are really in agreement with Mr. Cooper that the pipe forms a shunt to a portion only of the rail.

Since the paper was read we have received a communicatian from Dr. C. Michalke in which it is stated that the counter E.M.F.'s of polarisation encountered at the surface of the pipe at C and D in Mr. Cooper's Fig. D are dependent upon the current density, and are so variable that they cannot with any accuracy be taken into account. This agrees with our own experience, and we are of opinion that the increase of apparent resistance caused by polarisation is due to the isolation of the soil particles by means of minute bubbles of gas rather than to the counter E.M.F.

In conclusion, I would point out that our conclusions are not dependent upon strict parallelism of rails and pipes, as would appear to have been assumed by several of the members, such condition only being assumed for greater simplicity in explaining points which are already sufficiently involved.

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THE ELECTRIFICATION OF STEAM-DRIVEN NON-REVERSING ROLLING MILLS.

By W. F. MYLAN, Associate Member.

(*Paper received from the* LEEDS LOCAL SECTION, *March* 30, *and read at Leeds on April* 21, 1909.)

The advantage of electricity for power purposes has been appreciated by no one more than those engineers who are engaged in the production of the metals in all the varying forms which the requirements of the day call for. That such is the case, however, is a remarkable tribute to those pioneers who fifteen to twenty years back introduced the electric motor, at first with trepidation, and only as a means to an end for the supply of power at such points as it was impossible to reach with steam. The early workers applied the electric motor in substitution of steam on travelling cranes, isolated plants, etc.; but it was only after the electric motor in such situations had proved its remarkable reliability and economy that the more general application to live rolls, skid-gear, shears, punches, charging machines, hot saws, and other apparatus was carried out. Finally, having electrified every other part of the plant, the engineers naturally turned to the problem of driving the rolling mills themselves, and it is on this particular question that I present these few remarks to you to-night.

In the United Kingdom much has been done in this direction, but much more work remains to be executed. Leaving aside the question of reversing mills, which is a very deep subject, and which has deservedly met with a good deal of attention lately, the question whether to electrify or not to electrify a steam-driven non-reversing mill is one deserving our very closest consideration. Table I. gives a list of some mills now in operation in this country, together with information as to the type of rolls, size of motor, electrical characteristics of the power supply, and method of applying the motive power to the rolls. It is estimated that in Europe at the present date there are upwards of 230 electrically driven non-reversing mills in operation, the horse-power of the motors used exceeding a total of 200,000 H.P.

As indicated by this list (which represents only a selection), a large number of electrically driven rolling mills are in commercial operation at the present time, giving every satisfaction to the proprietor and justifying their conversion. As a consequence, and following on the data obtained from actual installations, the electric driving of rolling mills is now quite past the experimental stage,

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TABLE I.

Where Installed.	Description of Mill.	Motor.			Drive.
		Horse-power.	Speed.	Supply.	
Pather Iron and Steel Company	3 high 12-in. Merchant mill	500–1,000	375	3-phase, 25-period, 400 volts...	Ropes.
Etna Iron and Steel Company	3 high 12-in. Merchant mill	500–1,000	375	3-phase, 25-period, 400 volts...	Ropes.
Etna Iron and Steel Company	3 high 9-in. Merchant mill ...	250	485	3-phase, 25-period, 400 volts...	Ropes.
English McKenna Process Company, Ltd....	6 rail mills re-rolling old rails	500	290	3 phase, 50-period, 440 volts...	Double helical gears.
Excelsior Iron and Steel Company	Sheet mill	200	—	3-phase, 25-period, 400 volts...	Ropes.
Redheugh Mills	Sheet mill	350	375	3-phase 40-period, 400 volts...	Ropes.
Sir Theodore Fry...	Forge mill Merchant staff ...	400	330	3-phase, 40-period, 400 volts...	Geared.
	16-in. mill Merchant staff ...	250	385	3-phase, 40-period, 400 volts...	Geared.
(Being erected only)	10-in. mill Merchant staff ...	250	385	3-phase, 40-period, 400 volts...	Geared.
	8-in. mill Merchant staff ...	250	385	3-phase, 40-period, 400 volts...	Geared.
	16-in. rail mill	250	385	3-phase, 40-period, 400 volts...	Geared.
John Summers	3 high Merchant mill... ...	325	570	3-phase, 40-period, 400 volts...	Ropes.
J. Brown & Co., Ltd.	12-in. Merchant mill	200	200–450	230 volts (direct current) ...	Double helical gear.
J. Brown & Co., Ltd.	12-in. Merchant mill	200	200–450	—	Double helical gear.
H. Wiggins & Co., Ltd.	Sheet (nickel) mill	200	300	3-phase, 25-period, 440 volts...	Ropes.
H. Wiggins & Co Ltd.	Bar (nickel) mill	150	375	3 phase, 25-period, 440 volts...	Geared.
W. H. Moore & Co., Ltd.	Sheet (brass) mill	200	240	3-phase, 25-period, 440 volts...	Geared.
G. Johnson & Co., Ltd	Sheet (brass) mill	250	240	3-phase, 25-period, 440 volts...	Geared.
		325	365	3-phase, 25-period, 5,000 volts	Geared.
The Mint, Birmingham...	—	235	—	3-phase, 25-period, 5,000 volts	Geared.
		235	—	3-phase, 25-period, 5,000 volts	Geared.
Birmingham Metal and Munitions	Sheet (brass) mill	Two 110	360	3-phase, 25-period, 400 volts...	Double helical gear.
	Sheet (brass) mill	Two 160	360	3-phase, 25-period, 400 volts...	Double helical gear.
Williams and Robinson...	Tube mill	275	360	410 volts (direct current) ...	Ropes.
District Iron and Steel Company	12-in. Merchant and spoke mill	250	—	3-phase, 25-period, 440 volts...	Geared.
Jonas and Colver...	Bar mill...	200	500	2-phase, 50-period, 200 volts...	Belted.
British Insulated and Helsby	Copper rod mill	250	350–380	240 volts (direct current) ...	—
	Wire rod mill	130	388	3-phase, 40-period, 440 volts...	Geared.
Newcastle	Wire rod mill	130	770	3-phase, 40-period, 440 volts...	Geared.
	Wire rod mill	130	580	3-phase, 40-period, 440 volts...	Geared.

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and it is not only possible to estimate with certainty the size and every feature of an equipment, but to determine very closely the actual cost of operating under any stated conditions. Such a result has not been arrived at without careful experimenting, and great credit is due to those manufacturers who at considerable financial risk undertook the earlier work in this direction, and obtained the information whereby they are now able to offer a plant to run exactly in accordance with requirements.

The choice of a suitable equipment is all important, and whilst the description of several actual installations given later in the paper are of some interest as a guide, yet it must be remembered that every case requires separate consideration, and that an arrangement which would be sound in the one case would not be economical in the other. The problem of converting an existing installation is no simple matter, and very often the local conditions are such that the scheme decided on is only a compromise, the best proving unattainable. In many cases the difficulties have been further increased by the change having to be made with the minimum interference with the working of the mill, and it will interest you to know that such conditions have been successfully met, and the electrification carried through without any stoppage to the normal working of the mill. The essential part of the work was done during the week-end, and the smaller details and general clearing up executed at the ordinary stopping times. In one particular case no time whatever was lost by the mill during the conversion—a most creditable achievement.

In estimating for the electrical equipment of an existing steam-driven mill it is usual to take a series of continuous indicator diagrams of the engine, the mill for the time doing its hardest work. These diagrams are useful as a check from which to calculate the power of the motor to be installed, but great care must be taken not to place too great a reliance on the horse-powers as calculated from such diagrams. Allowance must be made for the increased output and heavier duty required of the motor due to the higher average speed, with consequent greater output following on the more even torque exerted by the electric motor as compared with the very uneven turning effort of the steam engine, and in these days it is better to estimate the horse-power of the motor by calculating the work it will be called upon to do from the data already obtained under the same or similar conditions. Knowing (1) the total output of the mill during a certain period; (2) the nature, size, and section of the raw material; (3) the size of the finished product; (4) the cycle of operations—that is, the number and time of the passes, and the period of rest—it is possible by comparison and from figures already known from other installations, to estimate very closely the horse-power of the motor to be installed.

A properly designed flywheel is of great assistance in reducing the size of the motor and enabling it to get over the peak loads without absorbing too great a current from the line. The tendency of the motor to slow down, due to a heavy load coming on, causes the flywheel

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to give up its energy, and as the load decreases and the motor speeds up energy will be returned to the flywheel. The ideal condition for a flywheel is when the highest load on the mill is accompanied by a reduction of the motor speed from the maximum to the minimum limit, so causing the flywheel to give up the greatest possible amount of energy, reducing thereby the demand made on the motor and by the motor from the line. This period should be followed by a light load period, allowing the motor to regain its normal speed and restore the lost energy to the flywheel. It should be remembered that the time taken to extract the energy from the flywheel is usually considerably shorter than the time required to return the same amount of energy to it, assuming that it is desired to maintain the demand from the line as nearly constant as possible. In the perfect case the light load period is equal to or greater than the overload period. The use of a flywheel for levelling the output demanded of the motor is not generally practicable if the time in rolling one pass exceeds about 30 seconds, and in such cases the introduction of a heavy flywheel would be open to very serious objections, inasmuch as the motor would, after a certain point in the pass, have to pull the flywheel round in addition to supplying the power required for rolling. This is the case in rolling long bars, rails, etc., and here a comparatively light flywheel is desirable, levelling only the smaller peaks and variations in the load, the motor being designed to deal with the main peaks without any external assistance.

In those cases where a heavy flywheel is employed with the object of relieving the strain on the motor it is usual to employ an automatic device to ensure that the flywheel carries its fair share of the load. With direct-current machines the motors are always compounded, but to increase further the strength of the field use is made of a separate excitation, which increases the field current, so reducing the speed still further and obtaining a return of the flywheel energy during the correct period. With alternating equipment a slip regulator is employed automatically, introducing a resistance in the rotor circuit at times of heavy load; the resulting effect, however, is the same and is independent of the electrical characteristics of the installation. As a general rule it can be stated that, with a properly designed flywheel, the fluctuations of loads are only one-half of what they would be were the flywheel effect not utilised.

The proper place for the flywheel is, of course, on the highest running shaft; but this is not usually feasible, and consequently it is generally found that the flywheel is fitted on a motion direct geared to the mill, thus preventing the extra strain on the motor and its gears or ropes.

Flywheel equalisers are occasionally employed to level up the demands on the power supply, but these are open to the same limitation as the direct use of a flywheel, and necessitate the motor being made large enough to deal with the maximum overload.

Regarding such machines and their uses, I would refer you to Mr. Peck's paper on this subject recently read before this Institution.

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In merchant mills it is an advantage and practically a necessity to be able to vary the speed of the mill motor. With a direct-current power supply this is a comparatively simple matter, and it is quite easy to obtain direct-current motors which are capable of giving their full normal output over a wide range of speed, the speed variation being obtained by means of field regulation only. In such cases the efficiency of the motor is to all intents and purposes unaltered by variation in speed, but unfortunately the same cannot be said where the source of power is alternating-current. As you are well aware, the only practical way of reducing the speed of an alternating-current motor is either by the introduction of resistance into the rotor circuit, or by choosing a suitable combination on the number of poles in the stator and distributing to stator winding to suit, to run at two or at the most three speeds with economy, these speeds being obtained according as the windings are connected to give one-half or one-third the normal number of pairs of poles. In the first case, speed reduction is obtained by means of, usually, a liquid type of controller, and over a very wide range, but with serious loss in efficiency (roughly the efficiency of an alternating-current slip-ring motor decreases in the same proportion as the speed decreases); and in the second case, a special controller grouping the stator windings in a suitable manner will give only two, or at the most three speeds, but give them with an efficiency only a few per cent. below the maximum. An attempt has been made to overcome the difficulty by adopting in cases where a speed reduction is desired a device in which the motor shaft carries a three-step rope pulley, and the necessary lengthened shaft is supported at its free end by a pedestal bearing, the whole being carried on a base plate mounted on slide rails. In the event of a different speed being desired, the motor bedplate is slacked back, the ropes changed to the desired group of pulleys, and the motor drawn back to tighten up the ropes. In order to carry this alteration through in the minimum possible time, a small motor is usually fitted to operate the sliding baseplate screws, and under such conditions it is remarkable what a short space of time is required to make a change. In an installation of this character the men are accustomed to make the change in some 3 or 4 minutes, this time representing the period under normal circumstances and without any special effort. Such an arrangement has the disadvantage that only certain predetermined speeds are possible for the mill, but against this may be set the fact that the motor is working at full speed continuously and consequently operating with the best possible efficiency, a most desirable condition.

The method adopted of transmitting the power from the motor to the mill rolls is worthy of careful investigation if the best possible results are desired from the change, and the opportunity should be taken to cut out any inefficient and unnecessary gearwheels, uneconomical drives, etc. Very often local conditions render it impossible to adopt that which is evidently the best, but usually some considerable economy can be obtained with the introduction of a new form of

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drive. In the large majority of cases it is impossible to couple the motor direct to the mill, and some form of speed reduction is essential. In such instances, however, where the motor can be direct coupled, it is advisable, with the view of reducing the sudden shocks and strains on the motor, to introduce a flexible coupling. The extremely favourable results which have been obtained by the introduction of such a coupling more than justify the extra expenses incurred, and there is, moreover, no difficulty in obtaining flexible couplings which are capable of standing the most severe service met with. The slow speed of a mill compared with the size of the motor required render it advisable in most cases, on account of capital cost and the difficulty in manufacturing slow-speed machines having really satisfactory electrical characteristics, to put in a high-speed machine and reduce by means of gears or pulleys to the required speed. Rope pulleys are often used to obtain this end, and have the same effect as the flexible coupling in the case of the direct-coupled motor. Where gears or direct coupling are adopted it is most important that the bearings of the motor should be properly designed, and also that the bearings of motors used in rolling mill work should be of more massive construction than is usual, and thoroughly well lubricated. With a properly proportioned bearing, a babbitted shell with ring lubrication is quite satisfactory, but on the larger sizes of motors it is sometimes desirable to introduce a proper system of forced lubrication with a suitable water-cooling device.

Owing to the heavy and frequent overloads that the motor must deal with, the shaft must be stiffened, and great care must be taken to see that the end windings of the motor are properly braced to prevent distortion. Where slip-ring motors are employed the rings should be of ample section. Occasionally one meets motors where the smallness of the rings has a serious effect in very much reducing the overload capacity of the motor owing to the smallness of the rotor currents, which can be dealt with without excessive sparking and heating at the rings.

A great feature of any electrical equipment is the ease and absolute certainty with which the control of the motor is effected. The provision of a suitable outfit of recording instrument is to be recommended. Such an outfit should consist of a recording ammeter or wattmeter, showing the momentary fluctuations in the load on the motor, and an integrating wattmeter totalling up the power taken over a certain period. By keeping a correct log of these data it is easy to determine accurately the cost of rolling each particular section. A circuit breaker should always be provided in the main circuit of the motor, the breaker being fitted with overload and no-volt release. The provision of a no-volt release is important, as this allows of the fitting of emergency switches at each housing or other suitable point, allowing the mill to be quickly stopped in case of necessity from any of several points. These emergency switches open circuit the no-volt release coil of the breaker, thus opening the breaker and cutting off the supply of current

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from the motor. For starting large motors, from all points of view a liquid controller is to be recommended. Such controllers, as now built, are highly satisfactory in operation, and require little or no attention beyond an occasional addition of clean water to the liquid. The sweetness of the start and the comparatively small floor space occupied more than counterbalance this little extra attention required. Large controllers of this pattern are usually fitted with cooling coils, the consumption of water for this purpose being about 3·3 gallons per hour per horse-power dissipated. For the best results the temperature of the resistance liquid should be between 60° C. and 80° C. Occasionally it is advisable to clean the controller thoroughly and to fill up with new solution.

I have been able to obtain particulars of several conversions which have been carried through successfully, and these will be interesting as covering mills actually in commercial operation at the present time which were originally driven by steam engines.

Cold Rolling Brass Merchant Mill.—This mill consists of one set of breaking-down rolls, one set of second breaking-down rolls, and two sets of finishing rolls. The breaking-down rolls are 20 in. diameter, 30 in. long, and all are driven at 6 revs. per minute by a long train of gear-wheels. Originally this mill was driven by a single-cylinder horizontal non-condensing engine, 28 in. diameter, 4 ft. stroke, and run with a boiler pressure of between 60 and 80 lbs. per square inch. The engine was fitted with an ordinary D slide valve and flyball throttle governor.

The usual size of ingots dealt with in this mill are 3 in. × 1½ in. × 7 ft. These ingots are rolled down to various gauges, No. 8 being about the average and also the usual size. In such a mill as described above, the ingot is first rolled into strip; this strip is then put through the cutting-up machine, resulting in pieces of rectangular section, which are then passed on to the draw benches to be drawn into ordinary brass wire.

In this case the motor is a 200-H.P. 25-period 400-volt 3-phase 240-revolution slip-ring motor, and it is direct geared, by means of cast-iron gear, to the mill. The gear ratio is about 4·8 to 1, the gears being 3½-in. pitch and 12-in. face.

In this case the motor is fed from the secondary of a 3-phase 5,000 to 400-volt transformer. No flywheel is provided, and consequently the overloads are dealt with directly by the motors. In this case the sustained overloads render a flywheel useless. Starting of the motor is carried out by means of a liquid starter, and an interesting feature is the installation of a number of emergency switches which, when used, open circuit the no-volt attachment on the primary switch (oil-break pattern) supplied. This equipment has proved extremely satisfactory in operation, and the ascertained consumption per ton of material dealt with have come well within the anticipated results. A feature of this equipment is the great saving of floor space occasioned by the installation of a motor in place of the original steam engine.

A better example of such saving is seen in the case of a similar mill. Here the motor has an output of 250 H.P. at 250 revs. per minute; it is

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of the slip-ring type, and in general exactly similar to the above outfit. The motor is direct-geared to the mill, and is placed underground, thus giving a very large additional flooring space, which, as this mill is in the heart of a large city and rather confined for room, is of the greatest possible value. This mill has two breaking-down rolls and six finishing rolls, as before driven by a train of wheels. The ingots dealt with are of brass 10 in. wide, 1 in. thick, and varying from 16 in. to 18 in. long.

The original engine worked with a boiler pressure of about 50 lbs. per square inch; had a single cylinder of 25 in. diameter by 4 ft. stroke, and ran at 53 revs. per minute. The engine ran condensing, and it is interesting to note that the condenser was much too small for the engine at full load. At no load the engine indicated 60 B.H.P., the average load was 120 B.H.P., and the maximum load 235 B.H.P.

The mill was designed for and deals with brass and white metal; the average output has been considerably increased since the mill was converted. It has been found on the average that breaking down 10 in. × 1 in. × 12 in. brass ingots into strips for wires takes 86 units per ton. This mill has shown a very large saving over the original equipment.

Iron and Steel Merchant Mill.—A mill rolling a large variety of sections has been in constant use for some three or four years, and as the result of the experience gained a second mill was converted to the electric drive. The sections of steel rolled consist principally of—

Rounds	...	... ¾ in. to 2⅛ in. diameter from 4-in. billets.
Flats	...	... 1 in. × ⅛ in. to 7 in. × 1 in. from old rails.
Squares	...	... ¾ in. to 4 in. from 4-in. billets.

The steels used are of varying hardness and range over from 0·2 to 1·2 of carbon.

The mill consists of 5 pairs of 12-in. rolls running at 80 revs. per minute as a minimum, and is driven through double helical steel gears, ratio 1 to 2·5. In this mill the 5 pairs of rolls practically comprise two mills having two gangs of men who work quite independently of one another. It thus often happens that several passes are made at the same moment, but as the motor is very generously rated no difficulty has been experienced through an exceptional load coming on and pulling up the motor. The supply in this case is direct current, and the motor has a normal output of 200 B.H.P. at from 200 to 450 revs. per minute. The machine is fitted with commutating poles, speed variation being obtained by the use of a field rheostat. As the rating of the motor is extremely liberal, overloads of 100 and 150 per cent. can be carried for fairly long periods without sparking or harm to the machine. The steam engine which this motor replaced was a very old beam engine, but this fact does not in any way discount the saving which has resulted.

Since the mill was electrified an increase of output of over 30 per

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cent. in material rolled and a decrease in the power consumed by 60 per cent. used has obtained. These figures have been ascertained by a careful log over a long period, and are certainly a remarkable tribute to the advantage of the electrical drive. The works in which these mills are installed have a very large power plant consisting of gas and turbine-driven machines, and consequently the cost of power per unit generated is very low.

Sheet Iron Mill.—A very good example of a mill of this pattern is being operated by a 350-B.H.P. slip-ring motor off a power company's supply. The mill has three pairs of housings of the two-high type barring, roughing, and finishing rolls, and deals on an average with 600-lb. blooms rolled into sheets 10 ft. × 4 ft. × $\frac{1}{16}$ in. The motor is designed to run normally at 400 revs. per minute when fed from a 3-phase 40-period 400-volt supply. It is fitted with rope pulley 4 ft. 6 in. diameter arranged for twenty-two 1½-in. ropes, the outer end of the shaft being carried on a pedestal bearing, and the whole carried on a bedplate and slide rails.

The control of the motor is effected by means of a hand-operated liquid starter and regulator, the controller being fitted with cooling coils as previously mentioned.

The motor drives by means of the ropes on to a second pulley 10 ft. 6 in. diameter and weighing 14 tons. The shaft of this pulley is geared to the mill ratio 1 to 3·75, giving a normal speed of the mill of about 45 revs. per minute. The gears are 17 in. face 4½ in. pitch.

Steel plates are rolled from billets, and in an actual case 2 billets each 3 ft. × 8½ in. × $\frac{7}{8}$ in. have been rolled into strips each 8 ft. 3 in. × 33 in. × 0·064 in. in from 120 to 150 seconds. This period covers 5 or 6 roughing passes and 12 to 14 finishing passes. The consumption of power in this particular mill was 6·5 units per pair of billets or 95 units per ton.

In a second example of work done by the same mill, the billets as before being dealt with in pairs, 2 billets each 4 ft. 2 in. × 10 in. × 1⅛ in. were rolled down in 8 or 9 roughing passes and 5 to 8 finishing passes to sheets each 8 ft. × 4 ft. × 0·080 in. at an energy consumption of 70 units per ton (10 units per pair of billets), the time for one rolling averaging 170 seconds.

Since having had experience of the above it has been decided to equip electrically a second and larger mill at the same works.

It is extremely difficult to obtain reliable figures as to the cost of rolling the different classes of material.

For purposes of comparison, however, it is useful to know the power consumption for rolling different classes of material and, knowing the cost per unit for the local condition, to arrive at some definite figure which will be a very close approximation to the actual power costs for a certain section. In any comparison of cost of rolling under the two methods of driving the only fair method of judging the relative merits is by the observation of the costs over a period; thus, in the case of a steam-driven mill including all stand-by losses,

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oil, waste, stores, and with the electrically driven mill making full allowance for the increased output or a similar output in less time.

For several of the figures given below I am indebted to the paper by Messrs. Koettgen & Ablett before the Iron and Steel Institute; other figures are given representing the actual ascertained consumption from certain mills as determined by careful calculation and observation made over a long period.

Rails and Girders.—Re-rolling 90-lb. rails of section 16 lbs. per yard, each piece 30 ft. long, required 56 units per piece. Total output of mill 4,800 pieces per 12 hours. Small mining rails rolled from billets 5 in. × 5¾ in. and weighing from 900 lbs. in the case of 28 lbs. per yard rails to an average of 650 in the case of 18-lb. rails required as follows per ton rolled: 28 lbs., 38 units; 24 lbs., 42 units; 20 lbs., 45 units; 18 lbs., 48 units. Smaller rails of 12-lb. and 8-lb. section require from 49 to 54 units per ton rolled.

Girders 11 in. × 6 in. can be rolled for about 50 units, per ton.

Channels averaging 1½ in. × ¾ in. × 0·02 in. require 66 units.

Angles 3½ in. × 3½ in. × ⅝ in. from 800-lb. billets require 50 units.

Sheets (iron) 8 ft. 3 in. × 33 in. × 0·064 in., 95 units per ton.
8 „ 0 „ × 48 „ × 0·080 „ 70 „ „
10 „ 0 „ × 48 „ × 0·067 „ 80 „ „
10 „ 0 „ × 48 „ × 0·125 „ 60 „ „
9 „ 6 „ × 42 „ × 0·09 „ 84 „ „

Breaking down 10 in. × 1 in. × 12 ft. brass ingots into strip about No. 8 gauge, 86 units per ton.

Rounds and squares: ⅞-in. rounds can be rolled at between 40 and 36 units per ton. The mill output is between 22 and 30 tons per shift. Average billet, 28 in. × 4½ in. × 4½ in.

1⅜-in. round bars required same power. Output of mill, 46 tons per shift.

Bars 1–2 in. and 1–7 in. diameter from billets 5 in. square require 38 and 40 units per ton. In this case the 1–7-in. bars were much shorter than the 1–2-in. bars, and consequently the consumption appears high.

Advantages.—As the torque exerted by the electric motor is maintained absolutely constant at a predetermined value and is quite independent of the momentary position of the motor, it is possible to run the mill at a considerably higher speed than formerly, and a better product with more uniform finish results. In one instance the speed of the mill has been twice increased, and this without any difficulty being met with in handling the material. In rolling at the increased speed it is found that though the speed is higher the rolls run more evenly, and the material coming away at a steady speed is quite easily caught and controlled when leaving the rolls. After a short time the men get accustomed to handle the product at the higher speed, and if on piecework prefer it, as enabling them to earn more money in the shorter time.

Due to this constant turning effort of a motor as compared with

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that exerted by a one or two-crank steam or gas engine, the electrically operated mills are very free from stalling; this is largely due to the smooth running of the electric equipment; but when a tendency to stall does occur the motor slows down, extra energy is obtained from the flywheel and from the line, automatically tending to get the material through the rolls.

The ability to run a mill at a higher speed, or at any rate to keep a more constant speed on the mill, allows a much greater output to be obtained from the mill during the same time as compared with the steam-driven mill, as owing to the good speed regulating characteristics of the motor the mill will make a greater number of revolutions during a shift than the corresponding steam-driven mill, consequently a bigger output is obtained for the same period. The large overload capacity, which is an inherent feature of all electric motors, enables a widely fluctuating load to be dealt with, the speed variation under very extreme conditions being decidedly small; this results in the mill running much smoother and more quietly.

An increased output can also be looked for due to the convenient and rapid manner in which the mill can be controlled and handled.

The efficiency of the electrically operated mill as estimated by the actual cost of rolling as compared with steam-driven mills is beyond dispute. In this connection it should be borne in mind that the actual decreased power costs in rolling are not due so much to the fact that it is an electric motor doing the work, but that the electric motor enables one either to purchase power at low rates from one of numerous supply companies who operate in all large industrial centres, thus shutting down the wasteful steam boilers and local electric plant, or, in the case of a number of mills, to concentrate the power plant at one spot, generate in bulk at the lowest possible cost, and distribute the power to the exact points required, with an economy unapproachable by any other system. In these advanced days most works have a large electrical plant installed, extensions to which do not involve a very large capital expenditure; but in those cases where no plant exists or where the plant is small and incapable of economical extension, there is no question that the cheapest method is to take power from the outside source.

A very important advantage which follows on the introduction of electricity is the possibility of arriving at very exact figures (not approximations) of the actual power consumed under any conditions. This information being obtained for each section rolled, enables a very close price for rolling to be determined, which in these days of extraordinarily keen competition is most desirable. From such figures also, by careful inspection, it is possible to tell at a glance whether the mill is in good working order, or by making alterations and taking readings, to see whether the best possible method of handling the material and obtaining the desired result is being adopted.

The extreme simplicity of the control and the ease with which it is possible to make electrical apparatus practically fool-proof, reduces the

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labour costs considerably, and this, coupled with the impossibility of an electrically driven mill racing, render less frequent the stoppages for broken couplings, pinions, and rolls.

Such troubles are inseparable from a stream-driven mill, and are a constant source of annoyance and a big loss, not only due to increased upkeep but to time lost by the mill having to stand whilst the repairs are carried out. The provision of simple and certain protective devices is easily arranged for, which in emergency can be relied upon to operate with certainty.

A very material saving in floor space is certain where a mill is converted to electricity, and this is a great advantage as it enables the space around the mill to be used for the more rapid handling of the material required to feed the mill, and for the disposal of the finished product. Very often the motor can with advantage be installed below the floor level, the only gear on the shop floor being the comparatively insignificant control gear.

An electrically operated mill has in any case less stand-by losses, and in the case of the motor fed from a supply company's main, none at all. In comparing the cost of rolling under the two systems (steam and electricity) this point is important, as in one case the losses are very serious and add largely to the total cost of rolling a certain output.

Where a motor is employed for driving a mill a great advantage accrues through being able to start up immediately, and a further reduction in cost of rolling is obtained through less labour being required to handle the same material. A motor requires only intermittent attention, and with emergency devices for stopping it is not necessary to have an attendant standing by continually.

Finally, on the question of capital cost, which, as in all engineering problems, has to be considered, speaking generally the actual electrical equipment of a rolling mill is at the worst only equal to, and in the majority of cases considerably cheaper than the corresponding steam equipment. If, however, electrification involves either the putting down of a generating plant or the extension of an existing plant, then there is no question that the electrification of the mill will entail the expenditure of a larger sum of money than that involved by putting down a new steam plant, and in such cases one must look in other directions to justify the conversion. Usually in any works having a rolling mill there are a great number of auxiliaries on which the existing drive can, with considerable economy, be replaced by one introducing the use of a motor, and it is the extra and more even load due to these motors that will justify the installing of a generating plant of capacity sufficient to carry the load on the mill and in addition that due to the auxiliaries. It would be impossible to run a plant feeding one mill only and generate with economy unless some other load less variable is also to be obtained, and consequently in such a case it is necessary to consider the broader scheme if any benefit from the electrification is desired. In the case of the works where a plant

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is already installed, and a comparatively cheap extension is all that is necessary, the problem is much simpler, and there is no difficulty in making out an excellent case for the electrification.

Supply companies in many areas are a ready source of power for such works as have not or cannot justify the installation of their own plant, and offer a convenient and easy means to the electrification of the mill. Many mills are already in operation under such conditions, especially in Glasgow, Birmingham, and the North-East Coast districts, and have proved to be entirely reliable, and operate at a much lower cost than under their old conditions. In one instance with power at 0·85 per kilowatt-hour a saving of over £3,000 was made on one year's working, more than paying for the cost of the equipment. The crux of the whole question of rolling electrically is whether or not a reasonably cheap source of power is obtainable either from a private generating station or from an outside source, and this obtained electrical rolling will be found to be considerably cheaper than steam, and the owners of mills and the shareholders will have reason ultimately to congratulate themselves if they decide to change over from the one method to the other.

Discussion.

Mr. Hartnell.

Mr. Wilson Hartnell: The author points out the convenience of driving rolling mills by electricity and the ease with which electric motors may be applied to non-reversing mills, and he gives examples of rolls that were at first steam driven but are now electrically driven, and of the advantages that have followed. The economies shown are, however, not solely due to the electric drive—some have arisen from its substitution in place of steam-gear that was rather antiquated. The ropes used are convenient, but involve a loss of about 7½ per cent. in power. Cut geared wheels of large size are now obtainable. At a works near Birkenhead for re-rolling steel rails successive sets of rolls are driven by electric motors and geared wheels. At the Prescot works of the British Insulated and Helsby Cables Company the set of rolls used both for aluminium and copper are driven through gearing by electric motors. A steam engine must be capable of exerting the maximum torque required on the rolls, which involves an expensive outlay. An electric motor capable of taking 100 per cent. overload for a short period is by comparison inexpensive, and the capital outlay to supply power is provided at the generating station. The steam engine requires a large and expensive flywheel to assist it to overcome the short overload. The flywheel of the motor, revolving at a much higher speed and assisted by the great overload capacity of the motor, is much smaller. The capital to be sunk to drive rolls by electric motors is therefore not only much less than that required for a steam plant, but, as the rolls are practically idle most of their time, the annual charge for interest and depreciation per ton of metal rolled must be much less when electric motors are used to do the same work. Steam plant for

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direct-driving reversing rolling mills is especially costly. As an instance, an engine at Sheffield of 8,000 H.P. with three cylinders made only a few revolutions backward and forward each time an ingot of steel was rolled. It was very interesting to see the manipulation of this plant, by electric motors, by some one in charge in a gallery. Nobody touched anything; the slabs passed backward and forward under the reversing rolls, and were occasionally gripped and turned edgeways or passed sideways to another part of the rolls, the rolls meantime adjusting themselves, and finally the floor rollers were set in motion and brought the bright hot slab to the hydraulic shears. We are all agreed as to the advantages of electrical driving. If, however, the Sheffield manufacturers were desirous of coming on to the Corporation supply, would the authorities be prepared to deal with at least 30,000 H.P.? Mr. Hartnell.

Mr. C. A. ABLETT: I think that Mr. Mylan has rather under-estimated the number of rolling mills which are driven electrically on the Continent, as I know that one firm alone has installed nearly 200 motors for driving non-reversing rolling mills, the aggregate power being nearly 200,000 H.P., and I believe that the total number of non-reversing rolling mills on the Continent of Europe which are electrically driven comes to nearly 400. With regard to the list of firms set out in Table I. which have adopted electrical driving, I could add about 10 names of English firms, and this goes to show how rapidly the electric driving of rolling mills is being adopted. As the question of reversing rolling mills has been raised in the discussion, I perhaps may be permitted to mention the equipment for a large reversing rolling mill which is being built for a plant near Middlesbrough. The mill motor will give about 10,000 H.P. under normal conditions of operations and is supplied by a flywheel converter set, and as this flywheel serves to neutralise the variations in load, the motor which drives the flywheel converter set has a capacity of only 1,800 H.P., and under normal conditions will be taking considerably less power than this from the power house. The question of economy has also been mentioned, and with regard to this it is of interest to refer to a large electrically driven reversing rolling mill which has been recently set to work in Germany. The motor is capable of giving 10,000 H.P. at 30 revs. per minute, and is, I believe, the largest reversing rolling mill motor in the world. I am told that the firm who own this mill state that the adoption of the electrical drive in place of the previous steam engine has saved them 1s. per ton rolled, and has enabled the output to be increased 30 per cent. Mr. Ablett.

With reference to the figures given on page 497, I would point out that, when the units per ton rolled for a given section are stated, the elongation should also be stated, because when the section is rolled from a large billet the power taken is naturally more than when it is rolled from a small one. Taking, for example, the 11 in. × 6 in. girders mentioned, the question might arise whether they have been rolled from a 4-ton ingot with a mean section of 19 in. × 19 in., or a bloom 10 in. × 10 in. If Mr. Mylan would add in every case the size of the ingot or bloom from which the sections are rolled, it would add very

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Mr. Ablett.

greatly to the value of the figures which he gives. As an example of this, I may mention that to roll out a 4-ton ingot measuring 19 in. × 19 in. down to a 10 in. × 10 in. bloom would take 11 or 12 units per ton, so it is a question if this should be added to the 50 units per ton which Mr. Mylan gives. Referring to the figures regarding the channels, I take it that this should read 1½ in. × ¾ in. × 0·2 in., and not 0·02 in., as given on page 497. It would also be interesting to know the size of the 800-lb. billets from which the angles were rolled, and also the size of the billets for the above-mentioned channels. The same remark applies to the figures for the sheets, although I believe this information is given for the 10 ft. × 48 in. sheets on the previous page. In the case of the 9 ft. 6 in. × 42 in. sheets, I think I can recognise this as a figure which comes from a paper read by Mr. Koettgen and myself before the Iron and Steel Institute, and so I can supply the size of the billets, which were 7·9 in. square, weighing 388 lbs. each.

Referring to the slip regulator, it is mentioned on page 491 that this is employed with an alternating equipment, and that the resulting effect is the same and independent of the electrical characteristics of the installation. I take it this means that the result is the same as with a compound-wound motor, but I should like to point out one very important difference; in both cases the speed of the motor must fall by some value up to 10 per cent. in order that the flywheel effect may be beneficially utilised, and while this fall in speed can be attained in the compound-wound motor without any loss of power, in the 3-phase motor a loss of power is necessarily involved. In the near future, however, a method of obviating this difficulty with the 3-phase motor may be found. In further reference to the question of the automatic slip regulator, I may point out that both with the alternating-current motor and with the direct-current motor there are two characteristic ways of obtaining the necessary variation in speed to enable the stored energy of the flywheel to be beneficially utilised in neutralising the peaks of the load:—

(*a*) Permanent slip regulation may be adopted in the case of the direct-current motor by providing compound winding, and in the case of an alternating-current motor by providing resistance in the rotor circuit.

(*b*) Automatic slip regulation may be provided in the case of the direct-current motor by relays which alter the resistance of the shunt field, and in the case of the alternating-current motor by an arrangement which automatically inserts resistance in the rotor circuit as the load increases.

The characteristic features of these two methods are: With the permanent slip regulation considerable variations in current about the mean value must take place, because it is the variation in current which causes the variation in speed, but the speed variation is not very great. Where automatic slip regulation is provided, the current always remains at practically constant value, corresponding to the

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mean value of power required, because the automatic slip regulator, when not actually in operation, may be regarded as being in a state of balance, and a very small variation in current is sufficient to upset the balance and bring it into operation. In this case, however, the variations in speed may be very great. It is sometimes stated that the use of the automatic slip regulator enables the losses which occur in the slip resistance of a 3-phase motor to be reduced, but practical experience has shown that no appreciable reduction can be effected. It is also mentioned on page 491 that the time taken to extract the energy from the flywheel is usually considerably higher than the time required to return it. It may perhaps be said in general that the conditions of rolling-mill driving are such that the time taken by the pass is considerably shorter than the interval between passes in many cases, so that more time is available for the flywheel to regain its stored energy; but I do not think it is justifiable to make any general statement that, apart from the conditions imposed by the process of rolling, the flywheel requires a longer time to regain its stored energy than to give it up. If the time of the interval is short compared with the time of the pass, the value of the mean power will be relatively high compared with the maximum, and so the flywheel does not have to give up much stored energy in order to equalise the load on the motor, and during the interval the power which the motor is giving is large, so that stored energy is being returned at a rapid rate. On the other hand, if the time of the interval is long compared with the time taken by the pass, the mean value of the power will be comparatively small compared with the maximum value, so that the flywheel has to give up a larger amount of stored energy in order to equalise the load, and although the motor is working at a lower power during the interval, yet the interval will be sufficiently long for the flywheel to regain its stored energy. When the permanent slip resistance is used, it will be found that, if the rate of giving up and regaining of stored energy be plotted against the time, logarithm curves are obtained somewhat similar to those of the heating and cooling of an electrical machine, but in spite of this it will be found in every case that the flywheel can regain the stored energy in the interval which it has had to give up during the pass in order to reduce as far as possible the variations in power required from the motor. With reference to the question raised on the top of page 494, about the use of the liquid controller for starting large motors, I am entirely in agreement with the author as to the desirability of using liquid controllers for starting 3-phase motors, but if a liquid controller was used with a large direct-current motor, I fear that, owing to electrolysis of the plates and of the liquid, considerable quantities of oxygen and hydrogen might be liberated, which would prove to be dangerous. Mr. Ablett.

Mr. A. J. CRIDGE: I have been much interested in the paper, and trust it will have some effect in extending the use of electricity for driving rolling mills in this part of the country. I can add some particulars of another mill to the list given by Mr. Mylan. The motor is supplied from the Sheffield Corporation's mains, and it is 350 H.P., Mr. Cridge.

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Mr. Cridge. 2,000 volts, 2-phase, 50 periods, running at 490 revs. per minute. The motor drives three sets of rolls, two by rope and one by belt transmission. A 4-ft. pulley on the motor is belted to a 10-ft. pulley on the 8-in. mill, and a 4 ft. 6 in. pulley is roped to a 14-ft. pulley on the two 10-in. mills. I am informed that, roughly, 30 to 40 tons of ingots of various sizes pass through the mill daily, with an average consumption of 1,050 units per day, so that the power used works out at from 25 to 30 units per ton. The author refers to 50, 84, and 95 units per ton, and the figures relating to the mill I have mentioned do not seem to be in agreement with those investigated by him. It would be interesting if the author gave us some information as to the method of controlling the speed of rolling mill motors by cascade connections. Would it not be difficult to drive one mill by two motors so connected? Further information about the flexible couplings referred to would also be of value. I notice that Mr. Mylan says rope driving is often used to obtain the same end, and I should think, from general considerations, this would be the better method.

Mr. Saunders. Mr. E. S. SAUNDERS: With reference to the figures quoted on page 497, stating the units consumed per ton, it appears to me that the first line and a half does not quite explain itself, "Re-rolling 90-lb. rails of section 16 lbs. per yard, each piece 30 ft. long, required 56 units per piece." I suppose that means 90-lb. rails down to a section of 16 lbs. Is it 30 ft. of the 90 lbs., or 30 ft. of the 16-lb. rails? If it is 30 ft. of the 16-lb. rails, then the 56 units per piece work out at 780 units per ton, and if it is 90 lbs. they work out at 140 units per ton, both of which are excessive figures. On page 498 the author states that the freedom from stalling is largely due to the smooth running of the electrical equipment, and that when a tendency to stall does occur the motor slows down, extra energy is obtained from the flywheel and from the line, automatically tending to get the material through the rolls. I do not think this is as plain as it might be. The freedom from stalling is really due to the enormous torque which can be obtained instantaneously from motors. I wish to advocate as far as possible the abolition of gear and rope between the motor and the mill. I notice that in the table given in the paper there is not a single instance of a direct-coupled mill. There is no real objection to designing a motor to run at almost any speed required, and direct driving is the most efficient way to drive a mill, and need not necessarily involve extra capital cost. Each case requires individual consideration. I quite agree with Mr. Hartnell that 7½ per cent. is constantly running to waste in cases where a rope drive is adopted, and in my opinion, if there is a double reduction gear, there is probably quite 10 per cent. running to waste. On page 499 the author states that a motor requires little attention, and with emergency devices for stopping it is not necessary to have an attendant standing by continually. I suppose that refers to emergency pushes which are installed in a number of accessible positions. I think every one will be aware of a case in Sheffield where a steam-driven mill was working which was fitted up

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lavishly with these emergency devices. One day the engine commenced to gain speed, eventually running away and bursting its flywheel with disastrous results. Not one single man had the common sense to use the emergency stops. Such an occurrence can easily be guarded against with electrical drives by means of automatic circuit breakers. Mr. Saunders.

Mr. T. H. CHURTON: The adoption of direct drive or gear drive is mainly a question of expense. In the case of driving by gear, whether ropes or not, a relatively high-speed motor may be employed, which is both more efficient in running and less expensive in capital outlay. Against these advantages is to be set the power lost in the gear, but this may be entirely balanced by the difference in the relative efficiencies of the high- and low-speed motors. With regard to the higher capital outlay in the case of the larger motor for direct driving, even if we assume that the efficiency is higher than that of the high-speed motor plus the gear, then the question whether this saving will or will not pay the interest on the extra capital depends on the price paid per unit for the power and on the load factor of the machine. For if the work done by the machine should usually run the motor at full load the return might be satisfactory, while under conditions which would entail the motor frequently working at relatively light loads, and therefore under less favourable conditions, the return might be insufficient to justify the extra outlay. As to the efficiency of rope driving, I am inclined to think that the 7½ per cent. loss that has been mentioned is higher than it should be for a well-designed drive. With regard to 3-phase induction motors for driving rolling mills, I note that those mentioned in the paper are all of the wound rotor type, whereas in my opinion the machine with the short-circuit rotor is pre-eminently suitable for this kind of work wherever its use is permissible on the supply system—that is to say, where the heavy starting current will not seriously affect the voltage of the supply. I know of motors of this type of from 50 to 60 H.P. being used for this purpose, connected to power companies mains, and giving satisfactory results. Mr. Churton.

Mr. H. E. YERBURY: I would like to ask the author why there are only three direct-current motor installations and twenty-six polyphase systems mentioned in the table, and also whether there is any special reason for this apart from the supply connections. In comparing the relative efficiency of steam engines and motors the author has, in my opinion, taken instances where inefficient steam plant was installed before the change. I notice one case where the average load on the engine was 120 B.H.P., and at no load the engine indicated just half, viz., 60 H.P., which leads one to think that undesirable friction and other losses were taking place, and it appears that in all instances very low boiler pressure was used. However, the author makes out a very good case in favour of motor-driven plant, and I certainly have no hesitation in supporting it. Mr. Yerbury.

Mr. W. F. MYLAN (*in reply*): I appreciate that the paper is open to extensive criticism. Mr. Hartnell referred to the question of flywheels, Mr. Mylan.

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Mr. Mylan. but the points he raised have all been dealt with by succeeding speakers. As regards electrically operated auxiliary gear, I called attention in my paper to the fact that electricity is extensively used in and about a rolling mill in all modern plants. A large number of cases can be cited where such plant has been in operation for ten or fifteen years, including several instances in this district. All these places have modernised their plants, using motors whenever they can, and it is very seldom a steam engine is met with in such works except for the mill itself. We do not claim that electricity is the "great save-all," for it is not. There are certain cases and conditions where electricity will lose money instead of making it, and as electrical engineers we ought to be the first to recognise this. I am glad Mr. Hartnell called attention to the question of auxiliary, because it is so remarkable to see the way in which the material is handled round a rolling mill without being touched by human hands. A youth stands on a platform with a number of motor controllers in front of him, by means of these he can move the material in any desired direction about the mill or to the next pair of rolls. One of the particular features of a steel works equipped in such a manner is the very small amount of manual labour that is required compared with the older and more cumbersome methods. Mr. Hartnell also referred to the rope drive. I quite agree that an array of ropes as viewed from the engine house is very imposing, but these ropes mean a lot of money. There are, however, times when the rope drive is the most suitable arrangement you can adopt.

I was pleased to hear Mr. Jones's remarks, as he has had actual experience in rolling mills, and is also among the few who have adopted direct-current motors for the mills. In his particular case they have been remarkably free from trouble. They have two mills at the present time in operation, the latter having been equipped as a result of the satisfactory operation of the first installation. I quite agree with him that we have not proceeded in this direction to the same extent as they have in Germany. The people of this country are new to the business, and are not likely to enter into any extensive alterations in general practice without considerable thought. Reversing mills have been mentioned, but this is a subject which requires separate treatment, for what is good with regard to non-reversing mills does not necessarily apply to reversing mills, and unfortunately we have only a few examples to refer you to. The whole question of units consumed per ton rolled is undoubtedly determined, as Mr. Ablett says, by the size and nature of the ingot at the commencement of rolling and the total elongation required. With an ingot of small section the cost per ton is lower than with one of greater section, because a lower degree of elongation is required to obtain the same section in the finished product. I am afraid I was somewhat misleading in my remarks on the subject of the slip regulator. What I really intended to point out was that energy is obtained from the flywheel in both cases irrespective of the method adopted to get it. Mr. Ablett is quite right in pointing out that an alternating-current motor has a

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Mr. Mylan.

lower efficiency than a direct-current motor when varied in speed below the normal, and it will be noticed that I specially mentioned that fact in the paper. The efficiency of an alternating-current motor is decreased practically in proportion to the decrease in speed when the regulation of the motor is attained by the introduction of resistances in the rotor circuit. With regard to the question of taking out and return of energy from the flywheel, the time required to return the energy to the flywheel is determined either by the maximum demand which can be made on the line or the maximum load which the motor will stand. There has been comparatively small progress made in regard to motors connected in cascade in this country. I know one instance where these motors are being used in connection with a small winder. For ordinary purposes the motors run in parallel. When it is desired to run at half-speed the rotor of No. 1 machine is coupled to the stator of No. 2. The efficiency of such an equipment at half speed and load is only 1 or 2 per cent. less than the normal full-load full-speed efficiency. I expect to see a large number of such combinations installed in the near future. It is possible to run at full load and full speed, or half load and half speed, with a high efficiency and comparatively good power factor. With regard to Mr. Saunder's remarks on the question of re-rolling rails, the matter on page 497 on this subject should read, "Re-rolling 90-lb. rails to a section of 16 lbs. per yard, each piece 30 ft. long." It should also read "56 units per *ton*." I quite agree that the absence of stalling is due to the fact that a motor has in itself a very large capacity for overload, and it is the combination of this with the smooth running of the equipment that gives freedom from stalling. On the question of direct-coupled motors, as mentioned by Mr. Saunders and Mr. Churton, it is not entirely a question of capital expenditure. Under certain conditions it is practically impossible for the manufacturer at present to build a satisfactory slow-speed alternating-current motor, the large number of poles which have to be put in necessitating a very large diameter. With a large diameter, if a machine is wanted which is not far too big for the output, or, in other words, very inefficient on normal load, naturally a very narrow machine is made. A machine of this type even then has a low efficiency and a very bad power factor, and under these circumstances it is far better to sacrifice a small proportion of the efficiency of a high-speed motor by gearing it down than to use a slow-speed motor with a low power factor, thus obtaining still lower efficiency by introducing extra losses in the line. Whilst there are cases of motors with high power factors under normal circumstances, manufacturers have not introduced a motor of slow speed having a really good power factor and efficiency. That is a serious objection, not only from the point of view of those firms that have their own power station, but from the point of view of the public supply company. In Sheffield the supply authorities refuse to allow a motor whose power factor is below their standard to be connected at all. There was a case in point recently. It was not a very slow-speed motor, but it was direct coupled, and there was great difficulty in

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Mr. Mylan. obtaining a motor with the power factor required by the Sheffield Corporation. I might say that they stipulate 80 per cent. or more on full load. In this particular instance the speed was about 200, and the horse-power about 70. Even at this comparatively high speed it was impossible to get the manufacturer to absolutely guarantee that it would give a power factor approaching 80 per cent. I believe the motor put in has not 80 per cent. power factor, but it was finally agreed to accept it, owing to the impossibility of procuring such a machine. This is an illustration of the great objection there is to slow-speed alternating-current motors. In the case of direct-current motors this objection does not hold good. If the price is immaterial one can get a motor of any speed you like, and with good electric and mechanical characteristics. In reply to Mr. Churton the whole question of direct-connected motors is a financial one, and the interest on the extra capital expense of the equipment must be balanced against the increased loss in efficiency which may occur. With regard to the use of short-circuit rotor machines, if Mr. Churton will give us a short-circuit rotor machine of large size which will start up against full load or rather more, while drawing only a reasonable current from the line, I shall be very pleased to sell them and watch them operate. The difficulty is in getting such motors of large horse-power to start up with less than twice full-load current on load.

With regard to Mr. Churton's remarks, I am sorry I cannot give you any definite information regarding the maximum size of short-circuit rotor machines in use, but I do know there are a large number of instances where such machines have been installed.

The subject of waste heat referred to is one which is attracting attention in many quarters, especially at Newcastle. It is rightly held that waste steam is money, and there is no district at the present time where this subject is being so closely watched as at Newcastle. Plants are in operation to a remarkable extent, utilising blast furnace gas or steam, which is supplied from boilers fed with furnace gas. In isolated plants the question whether the manufacturer should disregard the waste steam and take his current from the public supply has really no general answer, and each case must be considered on its own merits. The diversity factor is also difficult to give, because some mills are in a position to work several shifts a day and others only one shift, and some again are only working on and off, being entirely dependent on the trade conditions, and it is the latter point on which the diversity factor is dependent. Mr. Yerbury called attention to the large number of alternating-current motors which are used. That is to a certain extent due to the load conditions, and it must be remembered that in the majority of cases the power plant was in before the application of the power to the rolls, and alternating current was the main source of supply, and even now the majority of the supply companies selling current in bulk give an alternating-current supply. These two conditions account for the predominance of alternating-current motors.

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INTERPOLE DESIGNS.

By W. B. HIRD, Member.

(*Paper received from the* GLASGOW LOCAL SECTION, *April* 19, *and read at Glasgow on May* 11, 1909.)

The history of the use of interpoles in continuous-current dynamos and motors is a remarkable one, inasmuch as the device, although known for many years, has been put to no practical use until comparatively recently, and inasmuch as even now, when interpoles are becoming more and more common, such extended use is still meeting with considerable opposition from a number of designers, who would very strictly limit the field of usefulness of interpoles to special machines only, and would totally exclude them from use in machines for ordinary outputs at normal speeds. Considered from the point of view of interpoles or no interpoles, continuous-current designs fall into two distinct classes :—

1. Designs where the conditions are such that no satisfactory solution is possible without forced commutation of some kind.
2. Designs where the given conditions allow of a satisfactory solution without any special commutating devices.

In the first class fall generators and motors running at abnormally high speeds, *e.g.*, generators direct coupled to steam turbines or motors driving the modern type of high-lift turbine pumps. Also motors in which a high range of speed variation by means of shunt regulation is required. In both these cases the reactance voltage of the short-circuited coil becomes so high that commutation cannot be satisfactorily carried out without some special device. Broadly speaking, the reactance voltage of an armature is increased by increasing the length of the armature core relatively to its diameter, and also by decreasing the total magnetic flux of the machine.

In the case of high-speed machines the necessity for keeping down the peripheral speed requires a comparatively small diameter and correspondingly increased length, and therefore a high reactance voltage. In the case of variable-speed motors, the fact that the high speeds are obtained by reducing the total flux of the machine causes the high reactance voltage, and thus introduces difficulties in the design. In machines of the first class—*i.e.*, where the conditions are

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such as to make satisfactory commutation impossible or very difficult of attainment by means of designs on ordinary lines—the use of commutating poles has been found to very satisfactorily solve the difficulty. It is possible by the use of interpoles to work with values of the reactance voltage five or six times as great as would be admissible in an ordinary machine, and with careful design the results are entirely satisfactory.

In all the many papers and discussions dealing with interpoles there has been no great difference of opinion as to the advantages of the device for machines of this class. Although some designers prefer the use of a compensating winding spread over the main pole-face to the use of interpoles in high-speed generators, there has been a very general consensus of opinion that, for machines where forced commutation is necessary, the use of interpoles satisfactorily solves the problem. A very different state of matters exists, however, on the question as to whether the use of interpoles is legitimate in the case of those machines which can be satisfactorily designed without using any special commutating device.

The discussions which have taken place on this subject have been full of warnings as to the danger of introducing interpoles into general design merely because they were useful in special cases, and very strong and determined attempts have been made to restrict the use of interpoles to these special cases, the utmost concession made being that in certain cases they might be found useful in even comparatively small machines at ordinary speeds in order to obtain a specified output which happened not to fit readily into any one of a manufacturer's standard sizes.

Reference to the discussion on papers read within the last two or three years and to the technical press will show such an array of well-known names more or less strongly expressing these views as to render specific quotations unnecessary.

In spite of all these warnings from high quarters, the use of interpoles in normal designs—that is, in machines running at moderate speeds and of ordinary output—has been increasing and is becoming more and more frequent. It is also becoming more and more usual to find interpole machines specified by users who have had experience of them and prefer them to ordinary machines. This has been very generally described as merely an ill-considered and foolish following after fashion, but the continued trend to an increased use of interpoles in comparatively small machines appears to indicate that there is more in it than a mere fashionable whim, and it is to the use of interpoles in machines of comparatively small outputs and at ordinary speeds that I wish chiefly to direct your attention and invite discussion to-night.

Before proceeding to this, however, I will describe a simple method of arriving at the dimensions and windings of the interpoles. The literature on this subject is already of considerable bulk, but as the question of interpoles has not yet been brought before the Glasgow

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Local Section of the Institution, I will make no apology for briefly referring to it.

The principle of all interpole designs is to provide a small auxiliary pole between two main poles, in such a position and so proportioned that it will provide just such a field as is suitable for counteracting the reactance voltage of the short-circuited coil under the brush. The interpole is always series wound, and its winding carries the whole or a fixed proportion of the armature current; thus, so long as the iron is not saturated, the field strength under the interpole is always proportional to the armature current, so that if the design has been correctly worked out to give good commutation, say at full load, the same relation will hold between field strength and the armature current to be reversed at any other load, and the machine will work sparklessly without change of brush position at any load, the only limit being the saturation of the iron core of the interpole. That is, the machine will carry sparklessly and without change of brush position any overload up to the point where the increased ampere-turns on the interpole cause the iron to approach saturation.

One of the simplest formulæ for calculating the reactance voltage is that published by Mr. Mavor in a paper read at the International Engineering Congress in 1901; in this paper was also published the method of dealing with costs shown in Figs. 1 and 2. In a slightly modified form this formula is—

$$\rho = \frac{e\,c\,f\,m\,\pi\,l}{p\,n},$$

where—

ρ is the reactance voltage,
e the E.M.F. generated in the armature,
c the armature current,
m the number of turns in one section,
l the gross length of armature core,
p the number of poles,
n the number of magnetic lines per pole,
f the number of lines per unit length of core due to 1 ampere flowing in one turn of the short-circuited coil.

The value of f varies to some extent with the size of slot, the relative length of conductor in the slot, and in the end winding, etc., but for ordinary machines it does not materially differ from 20 lines per inch length of core.

The value of the reactance voltage given by the formula is the maximum value, and on the assumption that the current in the short-circuited coil varies as a sine curve the mean value will be $\frac{2}{\pi}\rho$, say $0{\cdot}636\rho$, and to obtain good commutation it is necessary that a field be provided under the interpole such as to generate a voltage in the short-circuited coil equal to $0{\cdot}636\rho$.

The number of turns in the coil is m, and if R be the number of

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revolutions per minute of the armature, D the diameter of the armature, and λ the length of the interpole measured parallel to the shaft, the E.M.F. generated in a magnetic field of density B will be—

$$m \times \pi D \frac{R}{60} \times \lambda \times B;$$

by hypothesis, this must be equal to $0{\cdot}636\,\rho$.

$$\therefore \quad m \pi D \frac{R}{60} \times \lambda \times B = 0{\cdot}636 \frac{e c m f l}{p n}.$$

$$\therefore \quad B \frac{\lambda}{l} = 0{\cdot}636 \frac{e c f}{p n \pi D \frac{R}{60}}.$$

If the interpole shoe is made of the same length as the armature core $\frac{\lambda}{l} = 1$, and the formula gives directly the value of B required in the interpole gap. It is usual, however, to make λ less than l whenever possible, the advantages being to lessen the leakage between interpole and main pole and also to minimise as much as possible the interference with the freedom of ventilation which an interpole extending over the whole length of core would produce. It should also be noticed that by decreasing the ratio $\frac{\lambda}{l}$ the value of B in the interpole air-gap is increased. If a very low value of B is used, there is no doubt that the reactance voltage of the short-circuited coil is increased by the presence of the iron pole-shoe, which decreases the reluctance of the magnetic path for lines surrounding the short-circuited coil.

If, however, the value of B is fairly high, this effect is much reduced, and the reluctance of the path and consequently the value of the reactance voltage is not appreciably affected by the presence of the interpole.

The width of the interpole shoe is not involved in the formula given above; it is determined by the consideration that if the coil undergoing reversal is in the interpole field for too short a proportion of the time of short circuit the reversal will not be properly carried out, whilst, on the other hand, the very considerable leakage which takes place between the interpole and the neighbouring main pole of opposite polarity make it advisable to keep the width as small as possible, so as to leave the actual distance from pole-shoe to pole-shoe as large as practicable. Various recommendations have been made as to the width of the interpole shoe by different writers. A width equal to one slot-pitch plus one tooth-width, calculated so that the coil shall be under the interpole during the whole time of commutation, and several much more elaborate formulæ have been published.

It would appear, however, in practice, at any rate in the case of machines where the reactance voltage can be kept down to reasonable limits, that considerable latitude is possible in the choice

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of a pole-width, and from the point of view of leakage the narrower the better.

The number of ampere-turns required on the interpole will consist first of a number of ampere-turns equal to the armature ampere-turns per pole. Since the interpoles are placed immediately over the brush—*i.e.*, on the axis of commutation—the whole of the armature ampere-turns act immediately in opposition to the interpole winding, and thus sufficient ampere-turns must be provided to neutralise the armature ampere-turns in addition to those required to give the requisite value of B in the air-gap. From this it will be seen that the number of ampere-turns required on an interpole are considerable. As a matter of fact, they are frequently in excess of the number required on the main poles. The fact, however, that the interpole can usually be made of small sections, so as to keep the mean turn of the winding short, enables this number of ampere-turns to be obtained with only a relatively small expenditure of copper.

The number of interpoles may be made less than the number of main poles. A 4-pole machine, for instance, may have only two interpoles. The field strength of each interpole must, in this case, be calculated to give twice the voltage which would be required if four were used, and a certain want of symmetry is introduced by such an arrangement of poles which has been found in practice to be detrimental to obtaining the best results, and although this arrangement of using a number of interpoles less than the main poles gives good results on small machines—say, 20-H.P. motors, in which the reactance voltage is not excessive—it has not been found satisfactory in machines of any considerable size.

To return to the question of using interpoles in the design of dynamos and motors of comparatively small sizes and working at ordinary speeds—that is, in cases where a good workable design can be obtained on ordinary lines—in order to justify this use of interpoles it must be shown that such a machine can by the use of interpoles be made either better or cheaper than could be done on ordinary lines of design.

To take first the question of cost. Since the material and labour expended on the interpoles make up, especially in a small machine, a not inconsiderable proportion of the total cost, a corresponding saving must be found in the other parts of the machine, due to the fact that the reactance voltage may be considerably increased without spoiling the commutation. The directions in which such a saving may be looked for are well known. They are the use of a reduced depth of air-gap, allowing of smaller magnets carrying less copper, reduced number of commutator parts, saving both labour and material in the commutator, and lastly, the possibility of working with a greater length of armature core relatively to the diameter.

The possibility of saving a considerable amount on the cost of any given machine by the latter means does not appear, up to the present, to have been fully taken advantage of. It is well known that in pre-

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sent practice the length and diameter are not chosen so as to give the machine most economical in first cost, and that greater relative length would almost invariably conduce to a lower cost price. If we consider a dynamo as consisting of two ends, the parts of the machine outside the two parallel planes which pass through the ends of the armature core, and of an active part included between these planes, and then vary the core length—*i.e.*, the active part—leaving everything else as before, and plot the cost of manufacture of different machines so obtained against core length, the points should be very approximately on a straight line, for every addition of, say, 1 in. in core length will mean an equal addition of material and of labour. The

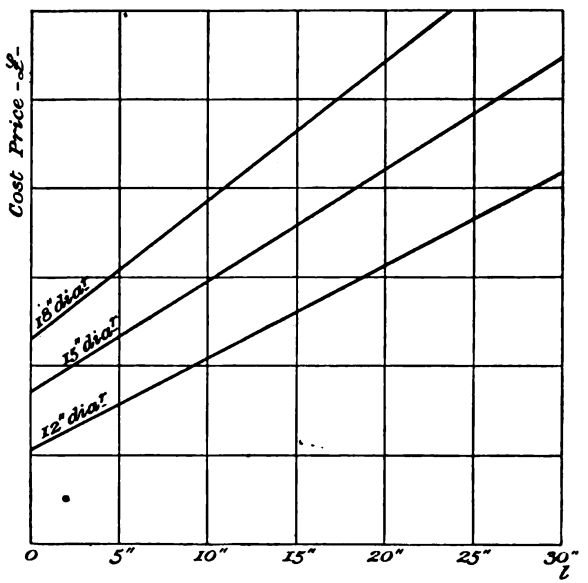

FIG. 1.

curve will remain a straight line with increasing lengths until a point is reached where the increased distance between bearings requires that the mechanical parts of the machine the shaft and bearings be strengthened, when a slight addition in cost will result.

The curves in Fig. 1 illustrate this, and show for the different diameters the way in which the cost may be expected to vary with the length of core. In Fig. 2 the same curves are plotted, but this time with d^2l instead of length as base line, and if it be assumed for the moment that the output of the machine, $\frac{\text{watts}}{\text{revs. per min.}}$, is proportional to d^2l, the points where these lines cross show the different lengths at which it is advantageous, from the point of view of economy in first cost, to pass from one diameter to the next larger

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diameter. The question of cost is acknowledgedly a difficult one to deal with in a general way, because costs are affected by so many local and other considerations unconnected with the design. It is believed, however, that these curves are fairly in accordance with ordinary present practice; they show only relative costs for the different diameters. The actual scale of cost price can be filled in for any individual line of machines, but the actual cost is unimportant for the present purpose; it is the relative cost of different lengths only which is of moment. The curves indicate that the economical lengths for the different diameters dealt with are considerably in excess of those

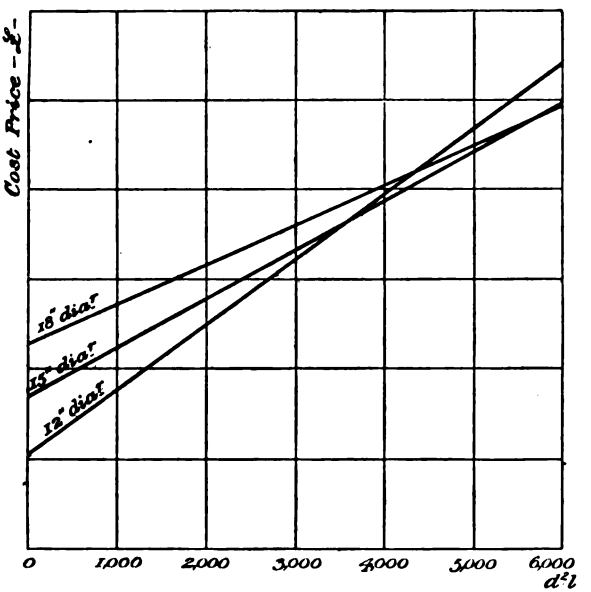

FIG. 2.

usually met with. Thus the value of d^2l, at which it becomes as cheap to make a 15-in. as 12-in. machine, is about 3,500, corresponding to a length for the 12-in. machine of $\frac{3,500}{(12)^2} = 24$ in., and the point where the 15-in. and 18-in. curves cross corresponds to $d^2l = 5,800$, or a length for 15-in. machine of $\frac{5,800}{(15)^2} = 26$ in. In any case, the point to be emphasised is that in any line of machines being manufactured such a series of curves, plotted with the actual figures obtained by experience, will show the most economical length of armature core for any given diameter, and it is believed that in the vast majority of cases they would show that the economical length is much greater than any at present in use.

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The statement, however, is true only on the assumption that the output increases proportionately to the length. In ordinary designs this assumption fails at once, because the increased length leads long before the economical length is reached to impossibly high reactance voltage; but if interpoles are used this sparking limit is removed so as to allow of, at any rate, a nearer approach to this economical length.

The question then arises as to whether the heating limit of output will not prevent the output of the machine being increased proportionately to its length. There is no doubt that a long armature core dissipates the heat generated less readily than a shorter one, and when the length becomes so great as to require increased diameter of shaft, stronger spider, etc., the increased impediment to the circulation of air in the inside of the core makes the increased temperature rise more marked. When this limit to output is reached it would appear that some method of forced ventilation compelling the air to come in contact with the heated surfaces might be devised to remove this limit to output also.

Forced ventilation has been repeatedly adopted in special cases for many years, and the possibility of a more general use of it whenever the heating limit of output was reached has been proposed on several occasions.

Doubtless there is not at present in use any system of forced ventilation at once sufficiently reliable and sufficiently cheap to meet the requirements of the case. Something more is wanted than merely stirring the air with fan blades—a definite circulation along a predetermined path is required; but if it be true that forced ventilation is the necessary consequence of forced commutation it may be confidently anticipated that such a system will be forthcoming.

It is true that in the past forced ventilation together with forced commutation has been generally looked upon with suspicion.

There is no doubt that the use of forced ventilation of a simple form—*e.g.*, by fixing fan-blades under the spider—and the use of forced commutation by interpoles has in many cases been adopted as an afterthought when a machine failed to come up to expectations on test, and perhaps from this fact has arisen a feeling that such devices were not legitimate and that their use in machines of normal output are a confession of failure to obtain a suitable design on ordinary lines. The contention here is that far from being a confession of weakness, such devices are an added strength in enabling a larger output to be obtained from a cheaper machine. Forced ventilation is used on transformers, why not in dynamos and motors? If interpoles are useful in enabling a machine to commutate in spite of a high reactance voltage when the conditions as to speed or output are abnormal, why should they not be used to obtain a normal output out of a smaller machine than would otherwise be possible?

The fact that interpole designs for normal outputs are becoming more and more common seems to show that the manufacturers using them find that they cheapen the cost of manufacture, and this, in spite

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of the fact that although the advantage to be gained by increased armature length is clearly recognised, no very striking departure has been made in the manufacture of machines with long armatures. Present interpole designs rely mostly on the saving to be obtained by the use of reduced air-gaps and smaller commutators with fewer parts, and find an advantage in their use even without taking full advantage of the increased lengths made possible by the use of interpoles. The reason is no doubt that the heating limit of output has been reached by them, but the fact that even then the use of interpoles is advantageous seems to indicate that if more ventilation can be obtained so as to further remove the heating limit of output, still greater advantage will be derived from the use of interpoles by making longer armatures. The possible output of a machine as limited by sparking having been increased by forced commutation, it is to be expected that heating should now be found the limiting condition, and the logical conclusion appears to be that the next step is to devise improvements in the methods of getting rid of the heat, so that full advantage may be taken of the increased freedom which the interpoles give from sparking limit.

There is further to be considered the question as to whether a machine for ordinary outputs will be improved or the reverse by the introduction of interpoles and by the modifications of design which such a use of interpoles involves. Electrically if good results are obtained in the case of machines such as turbo-generators which necessarily have a very high reactance voltage, there does not appear to be a good reason why equally good results should not be obtained on machines of normal output. The general experience of such machines now in use has been, on the whole, eminently satisfactory.

In designs on ordinary lines there is a great temptation from economical reasons to press up the reactance voltage to the highest limit which is considered safe, and to work with the lowest possible factor of safety. Thus it is not an uncommon experience to find modern generators working perfectly satisfactorily under ordinary circumstances, but having a reactance voltage so nearly up to the highest safe value that if the brushes are not in exactly the best position, or if the commutator has been allowed to get at all out of condition, they will flash over from brush to brush if the load be suddenly thrown off. Cases of that kind appear to be entirely removed by the use of interpoles, and there seems every reason to believe that an extended use of this method of construction would lead to better, not to worse, machines, as far as commutation is concerned. It may be true that there is some fear that mechanical troubles may arise with machines in which the air-gap is smaller, and the length between bearings greater than present practice. It should, however, be noted that suggested lengths of air-gap for interpole machines are still much greater than the very small gaps to be found in induction motors in which the mechanical difficulties have been successfully overcome, and also that the maximum lengths suggested still give a

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ratio of length to diameter much smaller than those commonly in use in the days of bipolar smooth-core machines. In view of these facts, it does not seem that mechanical difficulties need necessarily stand in the way of much longer armatures than we are at present used to with smaller radial depths of air-gap.

On the score of efficiency it may be contended that increasing the losses to such an extent as to require forced ventilation will lower the efficiency of the machine. But the increased losses correspond to a more than proportionately increased output and therefore to a better efficiency.

To take the case of proposed increased armature length. The losses which occur along the armature are iron losses, C^2R loss in that part of the conductors lying in the slots and windage, will be increased proportionably to the length, but the losses occurring in the ends of the machine, end windings, commutator, etc., will remain unaltered. The losses will therefore increase less rapidly than the length, and if an output proportional to the length can be obtained, the efficiency will be increased, and a margin left for the power required to circulate the air without lowering the efficiency from its former value.

Whilst it is admitted that the details of design frequently disclose unexpected difficulties such as to vitiate arguments based on general considerations only, it is submitted that the logical consequence of the use of forced commutation as it is actually at present employed appears to be a still further increase in armature lengths which may necessitate the introduction of forced ventilation, and that in this direction appears to be the means more immediately at hand of progressing towards the smallest and cheapest satisfactory machine for a given output.

Discussion.

Mr. Lackie. Mr. W. W. Lackie (Chairman): My first experience of interpole machines was not very happy. The characteristic of interpole machines is different from that of ordinary shunt-wound machines, and approaches to that of a compound machine. The result was that when we ran ordinary shunt-wound machines in parallel with a dynamo with interpoles, and overloaded them, the interpole machine endeavoured to do all the work, and thus sent a reverse current through the shunt-wound machines, operating the reverse-current cut-outs. Several methods of overcoming this difficulty have been suggested, one being to insert a resistance between the interpole machine and the switch-board so as to cause a drop in pressure when a heavy load is on. The method now usually adopted is to put one or two reverse series windings on the field of the machine. The other trouble with interpole machines is that if the brushes are moved or happen to be beyond the zone of the interpole the difference of potential per segment of the commutator is high, and flashing over takes place. On page 516 of the paper Mr. Hird refers to the question of forced ventilation, but I think it has been found that fixing fan blades under the spider is not always as economical as installing a separate fan. If the design is of a proper

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size to meet the output, simply fixing fan blades under the spider very frequently gives an inefficient fan. Mr. Lackie.

Mr. H. A. MAVOR: It is from people like Mr. Lackie that we manufacturers have to learn our business, and the points that he has raised are of very great importance in this most interesting subject. I resisted for a long time the suggestion of interpoles, because I looked upon this method from the point of view described by Mr. Hird, as a means for getting rid of troubles which should not be there. That was true in earlier days when the design of the machine was less understood, when no one ever thought of reactance voltage and the whole subject was wrapped in mystery, the real principle of design as now understood not having then been evolved, and therefore in considering the principle of interpoles we are in a somewhat different position from that of twenty-five years ago. It was about that time that Professor Ryan, of Bristol, first suggested a special wound projection for the purpose of reversing the current in the coil under the commutator. It is very remarkable that this invention should have been found useless and remained dormant for many years before being revived, and now be considered absolutely essential. I don't think we need yet be quite sure that it would not be better to increase the diameter of the machine, possibly using a less expensive material, and to force the output up by keeping the reactance down in that way rather than to keep the diameter down and put in interpoles for the use of high reactance voltage. The difficulty that Mr. Lackie has described would not arise in a machine of large diameter, but we are face to face with the difficulty that machines of large diameter are quite unsuited for use with steam turbines, and such a device must be used if these machines are to be run in parallel. Mr. Mavor.

Mr. W. MCWHIRTER: It is very interesting to the older members of the Institution to look back, as Mr. Mavor said, to the state of knowledge twenty-five years ago. Before we had the very splendid paper from Dr. Hopkinson we were very much in the dark regarding dynamo design. I think, as a matter of fact, it may be freely admitted we knew almost nothing regarding the work on which we were then engaged. It was at that time the usual practice to find some machine that gave fairly good results, and to keep as near to that as possible in future machines. Some short time ago we considered the question of the increase of output and decrease of the sparking troubles that used to be always present, and some of you will remember that owing to the use of carbon brushes it was then considered that we had about reached the limit of anything that might be expected; in fact, some of the speakers went so far as to say that carbon brushes had made such a change that the sparking limit was done away with entirely, and only the heating limit remained, and this is exactly the position given in Mr. Hird's paper. He increases his output by the use of commutating poles and suggests the use of a fan to get rid of the heating limit. No doubt this is a very important subject, and if the cost is kept down by the use of interpoles, the other advantages are great and lead to the entire Mr. McWhirter.

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Mr. McWhirter.

absence of sparking. On page 511 Mr. Hird gives a formula for calculating the reactance voltage. Now, as an outsider and not a mathematician, I would appeal to Mr. Hird and Mr. Mavor to try and arrange, if possible, to use such symbols that we have not to get up new notations in order to follow their calculations. Mr. Hird, like other writers, does not even stick to one set of symbols, but is evidently quite out of sympathy with his less learned brethren, and I would strongly appeal to him and to other writers that surely the time has arrived when some standardisation might be carried out regarding symbols for everyday use. Referring to his formula, Mr. Hird says: "For ordinary machines it does not materially differ from twenty lines per inch length of core." I have been wondering what the author means by the length of core. I would look upon the length of the core as being the length in the direction of the flux, but I must be wrong. Perhaps Mr. Hird will tell us what he means. I think he must mean the length parallel to the spindle. [Mr. HIRD: That is quite right.] The curves on page 514 are very interesting and look beautifully symmetrical, but I am afraid there has been a good deal of what we might call cooking about this. My firm have never had any trouble with interpole machines, but the same remark might also be made regarding machines generally since the introduction of carbon brushes. It is very rarely that machines give any trouble through sparking when they are kept in good order. A short time ago I had occasion to test a dynamo of about 80 k.w., and after running five hours at full load we increased the output until it was 50 per cent. overload, and during the whole of the test there was entire absence of sparking, although there were no interpoles, and I am certain the adoption of interpoles could not have improved the work of this machine in the slightest degree.

Mr. Nicholson.

Mr. J. S. NICHOLSON: If, as Mr. Hird says, the output of the machine is limited by heating, then it would be better to try and eliminate the heating, instead of putting a fan to carry off the heat. The way in which designers or manufacturers should work is to get a better class of material for the armature core. A great deal has already been done in that direction by steel manufacturers, and I think this is the proper way to work. With better iron it is possible to get much less heating in the armature.

Mr. McMillan.

Mr. CAMPBELL MCMILLAN: Mr. Mavor has spoken of Mr. Hird's association with him in the design of electrical machines, and I once had the privilege of being his subordinate and his understudy and of using his methods for some time, but I have departed a good deal from the habits of that time. Since leaving the design in the machinery such as Mr. Hird has referred to, I have had occasion to look a little closer into the costs of machines of various types, such as large induction motors up to 6,000 H.P., and to attempt to deduce from the dimensions and details some empirical laws or formulæ for obtaining costs, and one of the points which appeals to me is contained in the paragraph which says, "In this direction appears to be the means more immediately at hand of progressing towards the smallest

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and cheapest satisfactory machine for a given output." The fact that must be looked closely into is the size of the machines dealt with. Below a certain size of machine it will not pay to use such refinements as extra forced ventilation. When supplying large machines it may obviously be quite a minor matter to add the necessary plant to produce efficient forced ventilation. What I want to point out is that if the curves applied to a size of machine which could be ventilated artificially, then the point would be completely carried. I would, however, like a little more information from Mr. Hird as to whether these curves are so based on actual experience with a large number of machines that we can take them to fairly represent the commercial facts of the case, or whether they apply more directly to a certain limited range of design, and whether that range is one in which he would propose to use an auxiliary for the purpose of forced ventilation. Not only did we go into the question of the complete cost of the machine, but also into the cost of the various parts, and into some minor questions to which he refers, such as the facts that a certain stage he added to the strength of the shaft to deal with the larger weight of armature. Some of these are more important than would at first sight appear, and they begin to affect the matter so early that they vitiate the simplicity of the laws which are indicated by these graphical results. In the range of machines with which Mr. Hird wishes to deal it seems self-evident that the lines which he has indicated ought to be followed as closely as possible by designers. Perhaps the most practical thing that has been done with forced ventilation in machines of small size is its attempted application to railway motors. It would be interesting to hear from any member what success has attended these efforts, as the results are not readily accessible. The necessities of the case in the development of single-phase motors has also pressed designers to forced ventilation, and I think that line should be followed up more closely in single-phase electrical traction propositions. In using curves to indicate the cost, and especially where they are used to indicate the minimum cost, it is better to follow the matter closely and see how slightly the factors are changing. On each side of a minimum value are other values which differ so slightly from it that the difference is more than covered by the possible errors in cost estimating. For this reason the true minimum is difficult to ascertain even approximately. In the same way, any data depending on the point of crossing of two estimated lines which cross at an acute angle are of very uncertain accuracy indeed. Mr. McMillan.

Mr. HENRY A. MAVOR: The working out of cost by means of curves is one in which I have taken a very great interest, and what Mr. McMillan has said suggests to me a warning to young engineers dealing with such problems, that they must not expect to get from the curve any such results in the matter of cost as in geometrical problems. The terms used by Mr. McMillan suggest to me that his point of view is not quite safe, that in plotting records of costs by curves one has always to bear in mind that one is engaged in trade where not only such things Mr. Mavor.

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Mr. Mavor. fluctuate, as Mr. McMillan has mentioned, but other things fluctuate very much more. Wages may fluctuate—in fact, the time of the year in which the machine is made affects its cost as much as a small change in the dimensions, and therefore engineers starting in business must carefully bear in mind that in dealing with costs of machinery by curves in this way one must not expect to get within 10 per cent. of the price. I mention that figure to give an idea of the probable amount of error. The only sound way to deal with costs is to take a curve and strike it through reasonable expectations; then make a plentiful allowance for contingencies and on cost, and take any profit available; but do not think it is possible to find out the cost of the machine by curves such as those of Mr. Hird, without the reservations which I have indicated. From a commercial point of view (and it is that point of view that any manufacturer must have most prominently before him) the best machine is that which is flexible and in which the engineer can adopt either of these expedients. With regard to the other saving mentioned in the paper, due to increasing the length of the machine, the advantage of this is somewhat questionable, as in a small diameter machine the active material is relatively larger and the inactive smaller than with a larger diameter of the same capacity. The final result would, however, be practically the same.

Again, speaking commercially, a machine having an armature 12 in. × 24 in., or 15 in. × 26 in., as mentioned by the author in the paper, would be debarred from a large number, if not a great majority, of markets on account of its inadaptability to the requirements and position in which it was to be used. This would apply very strongly to such work as fan work on ships, or where floor space was a question of importance. Of course, the long tubular design might be all right where the surrounding conditions are prepared for it, as in the case of a turbine generator, but a motor is an essentially adaptable article and has to go often into wherever it can be squeezed. If, by stress of circumstances, motors were forced to take this elongated form, their natural position would probably, in course of evolution, become perpendicular with vertical shafts, which would, of course, take away a lot of wear and friction, but the difficulties of driving would be very great.

Mr. Tidd. Mr. E. GEORGE TIDD: On reading through the paper, one gets the idea that the author has discovered a kind of conspiracy against the use of interpoles, but I must say that I have not noticed it. In my opinion the up-to-date designer regards the interpole machine as a standard from his point of view, and in these competitive times he will economise in his design, if possible, by omitting the interpoles, and the opportunities where he is enabled to do so are relatively numerous. The author refers to two directions in which a saving can be effected: by the use of a reduced depth of air-gap, or reduced number of commutator parts. It is, however, dangerous to economise by reducing the air-gap, as interpoles do not cure distortion, and it is very doubtful if they recede the flash-over point to any extent if the

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machines are properly designed. It seems to me that it would often be cheaper to put in a somewhat larger commutator with a greater number of sections and leave out the interpoles, than *vice versâ*. Mr. Tidd.

Mr. J. R. BARR: The author has examined some of the factors which have been brought into prominence by the application of interpoles to machines of normal ratings and speeds, but I question if the conclusions arrived at may be regarded as perfectly general. Mr. Hird states, "In order to justify the use of interpoles it must be shown that a machine can by their use be made better and cheaper than could be done on ordinary lines of design." This, I think, puts the whole problem of "interpoles or no interpoles" in a nutshell. If a machine has to be built to fulfil a specification of output at given speed, efficiency, and temperature rise, then the best design will be the one which, for the same quality of materials and workmanship, fulfils the specification with the minimum expenditure on labour and material. The author has given three reasons why a design with interpoles will be cheaper than one without interpoles; they are :— Mr. Barr.

1. The value of d^2l will be smaller.
2. Less copper is required for the main field windings, owing to the smaller length of air-gap possible.
3. Since the reactance voltage is neutralised by the commutation field more turns per segment are possible and therefore a smaller number of segments.

There is a fourth argument in favour of interpoles which Mr. Hird has not mentioned, namely, that by using brushes of lower contact resistance the commutator C^2R loss will be less, thus further reducing the cost of the commutator.

We now look to some important considerations on the other side of the balance-sheet. By inserting interpoles between the main poles the leakage flux of the latter will be nearly doubled, and to balance this there must be a proportional increase in the field copper. As regards the question of heating in a motor or dynamo fitted with commutation poles the output is entirely limited by thermal considerations. Now the very use of interpoles fills up the space between the main poles and so reduces the thermal capacity of the machine, and without the use of any extra ventilating devices I have found that the thermal limit of output under such conditions may in some cases be less than the commutation limit of the same machine without interpoles. To overcome the heating difficulty to a certain extent, Mr. Hird has proposed the use of fan arrangements which would further add to the cost. It will thus be seen that the diminished cost in the first instance has been largely balanced by the auxiliary apparatus necessary both for commutation and ventilation. It is my experience that for correctly designed machines of moderate speed and output there is nothing to be gained by the use of interpoles, which in such cases only add needlessly to the cost and actually decrease the efficiency. Of course, there are special cases where commutation poles are necessary—*e.g.*, variable speed

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Mr. Barr. motors and high-speed generators—but this is no reason why they should be used indiscriminately for all types and sizes.

Mr. Pearson. Mr. T. PEARSON: With reference to ventilation, I would ask if water has been tried for cooling. It would be simpler than air, and would circulate in a hollow shaft similar to that used in a gas engine, and it would be applied to the magnetic field. I would be glad to know if any one has tried this. It seems that it is an easier way because the cooling power is obtained without having to expend power, and it is necessary to expend power to cool by means of air.

Mr. Mackenzie. Mr. J. D. MACKENZIE: I should like to emphasise the point raised by Mr. McWhirter with regard to formulæ. In reading over text-books dealing with electrical matters, the various formulæ which I meet with are something appalling: no two authors are ever quite the same. I think it is a point which ought to be strongly emphasised that some definite standard of formulæ should be used by all writers on the same subject.

Mr. Hird. Mr. W. B. HIRD (*in reply*): Several points of great interest have been raised in the discussion. The first one is a question of running a machine fitted with interpoles in parallel with an ordinary shunt-wound dynamo. It may be pointed out that if the practice of fitting interpoles on all large generators becomes universal, the difficulty will gradually disappear as the number of dynamos not provided with interpoles becomes smaller. What difficulty does now arise is due to the two machines having different characteristic curves, and the remedy mentioned by Mr. Lackie—*i.e.*, putting a few reverse series turns on the main poles—gives the designer such control over the characteristic curve of the interpole machine as should obviate any trouble whatever in putting it in parallel with any other machine.

I am in agreement with Mr. McMillan that on each side of the minimum point on curves of cost such as appear in the paper, "are other values differing so little from the minimum value that the difference is more than covered by possible errors in cost estimating." My suggestion was not that machines should be made as long for a given diameter as indicated by the curves, but merely that the core-lengths indicated are so much in excess of what is now usual that there is evidently room for very considerable increase in length without approaching the region of the curves where they become doubtful, and that such an increase would make for economy. This also answers Mr. Mavor's objection as to the great length of the machine making it unsuitable for many positions on account of the floor space taken up.

The question of forced ventilation has been referred to by several of the speakers. There is no difficulty in providing forced ventilation in machines so large that a special plant can be provided without undue increase of cost; it is in small machines that the difficulty arises, as the cost and power taken by the ventilating mechanism must be kept very low.

I sympathise with those gentlemen who deplore the fact that there is no universally accepted system of symbols, and I shall be most careful to use such a system as soon as some authorised body gives us one covering the quantities I wish to refer to.

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THE GERMAN STANDARDS AND REGULATIONS FOR ELECTRICAL MACHINERY.

By NORMAN C. BRIDGE, Associate Member.

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INTRODUCTORY NOTE.

Attention was called last year to the rules of the Society of German Electrical Engineers ("Verband Deutscher Elektrotechniker") by Mr. W. P. Steinhal in a paper * read before the Leeds Local Section of the Institution. This paper dealt with electric installation work, and contained a translation of the German rules and standards applying to this class of work.

The complete publication of the Verband Deutscher Elektrotechniker—the Standards, Regulations, and Directions ("Normalien, Vorschriften und Leitsätze des V.D.E.")—covers a much wider scope, and represents a very large expenditure of time and labour in formulating regulations and standards for various purposes connected with the electrical industry. The work has been undertaken by various commissions appointed by the Society from time to time, whose recommendations were originally published only in the official organ of the Society—the *Elektrotechnische Zeitschrift*—or, in some cases, in pamphlet form as well.

In 1903 the first edition of the complete publication in its present form was brought out by the Society under the editorship of Dr. Gisbert Kapp, at that time General Secretary.

A second edition was published in 1905, and a third in 1907. The progress of the industry has necessitated revisions in certain sections, and the further regulations and standards formulated by subsequent commissions and approved by the Society at their annual meetings have, of course, been added in the later editions.

With regard to the two sections here translated the regulations referring to the connection of motors to public supply systems appeared for the first time in the 1907 edition of the German Society's publication, but those referring to the rating and testing of electrical machinery appeared originally in the first edition, and were revised for the 1907 edition.

Both these sections came up again for revision at the annual meeting held at Cologne in June of this year, and the amendments agreed upon have been embodied in the translation. The most interesting

* *Journal of the Institution of Electrical Engineers*, vol. 41, p. 166, 1908.

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change is in regard to pressure tests, the new requirements of § 26 showing a complete reversion to the British and American method of flash tests instead of time tests. The previous requirements were a test lasting half an hour instead of a minute, and a pressure determined as follows :—

Working Pressure.	Test Pressure.
Up to 5,000 volts.	Twice the working pressure.
5,000 to 10,000 volts.	Working pressure plus 5,000 volts.
Above 10,000 volts.	1½ times the working pressure.

In § 32 the minimum test pressure for field-magnet coils has been altered from 100 to 1,000 volts.

(*Translation.*)

STANDARD REGULATIONS FOR THE RATING AND TESTING OF ELECTRICAL MACHINES AND TRANSFORMERS.

DEFINITIONS.

A "Generator" or "Dynamo" is any rotatory machine in which mechanical energy is converted into electrical energy.

A "Motor" is any rotatory machine in which electrical energy is converted into mechanical energy.

A "Motor-generator" is a double machine, comprising a motor and a generator in direct mechanical connection.

A "Rotary Converter" is a machine in which a conversion from one current to another is effected in one common armature.

The term "Electrical Machine," or simply "Machine," will be used hereafter to denote any of the above, according to the context.

An "Armature" is that part of an electrical machine in which an electromotive force is produced by the influence of a magnetic field.

A "Transformer" is an alternating-current apparatus, with no moving parts, in which a transformation of electrical energy is effected.

The "Pressure," in 3-phase circuits, is understood as the effective phase volts (voltage between any two of the three main conductors).

The "Star Pressure," in 3-phase circuits, is understood as the voltage between the neutral point and any one of the three main conductors.

The "Ratio" in transformers is understood as the ratio of the voltages at no load.

The "Frequency" is understood as the number of complete alternations per second.

The "Volt-amperes" is understood as the product of the current, voltage, and phase multiplying factor.

The foregoing definitions, which refer to alternating currents, also hold good, as far as they can be applied, for polyphase systems.

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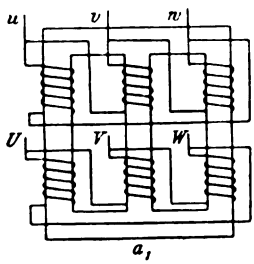

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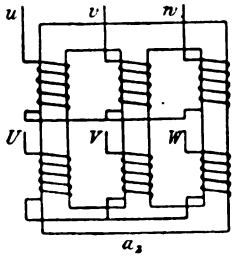

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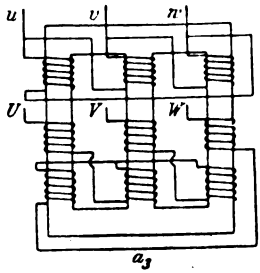

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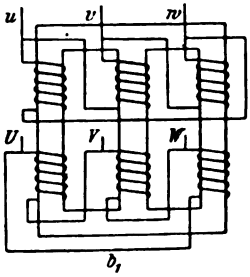

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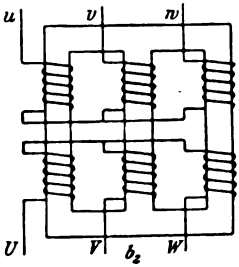

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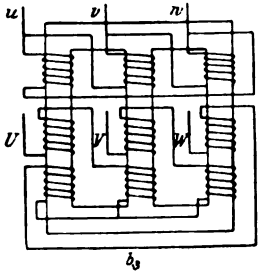

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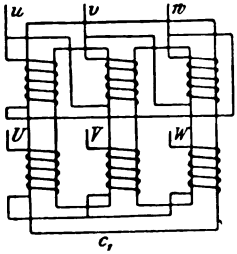

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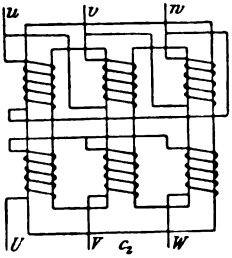

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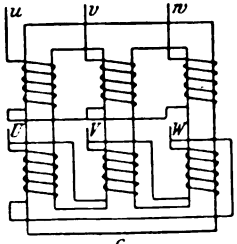

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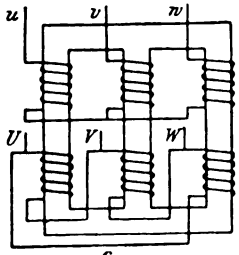

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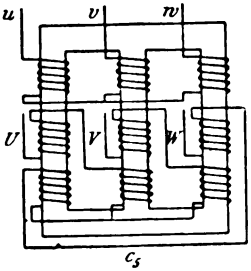

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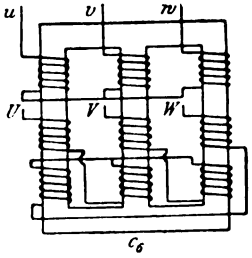

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General Statements.

§ 1.

The following regulations apply only in so far as they are not modified by any mutually agreed upon conditions of contract.

This does not, however, apply to the regulations referring to the "Output-Plate" (cf. §§ 4, 5, and 6), which must be filled in in every case.

Machines and transformers with no output-plate, or with any plate differing from that further prescribed below, will not be considered as conforming to these Standard Regulations.

Output.

§ 2.

The "Output" in all machines and transformers is taken as the power given out. This shall be stated, for continuous current, in kilowatts (K.W.), and for alternating current in kilovolt-amperes (K.V.A.), with a statement of the lowest safe power factor. Statements of mechanical output shall be given in horse-power (H.P.).

In addition to the above, the normal speed, equivalent frequency, voltage, and current values shall be marked on the output-plate, and also, in asynchronous motors, the voltage at the slip rings on starting up.

In transformers the voltages stated upon the output-plate shall represent the ratio (at no load).

In 3-phase transformers the arrangement of windings must be distinguished by a letter as belonging to one of the following characteristic groups, in which the various connections of terminal leads are suitable for working in parallel.

§ 3.

With regard to the output, the following methods of working are to be distinguished :—

(*a*) "Intermittent Working," in which there are alternate periods of working and of rest, each of 1 minute's duration (*e.g.*, in motors for cranes, hoists, tramways, and so on).

(*b*) "Short-period Working," in which the period of working is too short to allow of the final temperature being attained, and the period of rest is long enough to allow of the temperature falling again to practically that of the atmosphere.

(*c*) "Continuous Working," in which the period of working is long enough to allow of the final temperature being attained.

§ 4.

For Intermittent Working the normal output of machines and transformers shall be understood and stated as the power which can be developed continuously over a period of 1 hour, without the tempera-

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ture rise exceeding the values hereinafter stated as permissible. This output shall be stated on a plate, and designated as "Intermittent."

§ 5.

For Short-period Working the normal output of machines and transformers shall be understood and stated as the power which can be developed over the period of working agreed upon, without the temperature rise exceeding the values hereinafter stated as permissible. This output shall be stated on a plate, and designated as "For . . . hours."

§ 6.

For Continuous Working the normal output of machines and transformers shall be understood and stated as the power which can be developed over a suitable period, without the temperature rise exceeding the values hereinafter stated as permissible. This output shall be stated on a plate, and designated as "Continuous."

§ 7.

The different outputs for the different methods of working may be stated.

§ 8.

In generators and rotary converters with fluctuating voltage it is sufficient to state on the plate the normal values of the voltage, current, and speed; the respective limiting values must, however, be stated in the contract specification.

§ 9.

Machines with commutators must run so sparklessly at all loads within the permissible limits that with the brushes run smooth and adjusted in the most favourable position an application of glass-paper, or the like, on the commutator is only necessary at most after each 24 hours' running.

The position of the brushes shall remain thus unaltered for load variations from a quarter-load to full load.

Temperature Rise.

§ 10.

The temperature rise of machines and transformers at normal output and under the conditions of the methods of working described above shall be measured thus :—

1. For Intermittent Working, after 1 hour's continuous running.
2. For Short-Period Working, after continuous running for the time specified on the output-plate.
3. For Continuous Working—
   (*a*) In machines, after 10 hours' running.
   (*b*) In transformers, after running for the time required for the temperature to reach a constant value.

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§ 11.

In very small machines, where it may be taken for granted that the constant temperature is reached in less than 10 hours, the temperature rise may be measured after such a shorter period as may be specified.

§ 12.

When testing the temperature rise the ordinary covers, lids, cases, and so on, of machines and transformers may not be removed, opened, or otherwise altered to any appreciable extent. Any means of cooling dependent on the actual running of a machine in service, and allowed for in the design, may, in general, be reproduced artificially on the test, although in the case of tramway motors it is not permissible to reproduce in this way the draught due to the travelling of the car.

§ 13.

The air temperature shall be taken as the temperature of the current of air flowing in, or, if there is no appreciable current, as the mean temperature of the air at the level of the centre of the machine, the measurement being taken in either case at a distance of about 1 metre from the machine. The air temperature during the last quarter of the test period shall be noted at regular intervals, and the mean value obtained therefrom.

§ 14.

In using a thermometer to measure the temperature it is necessary to establish as good a heat conductivity as possible between the thermometer and the part of the machine being tested, as, for instance, by means of tinfoil wrapping. In order to avoid any loss of heat the bulb of the thermometer and the point of measurement should, moreover, be covered in with a bad heat conductor (dry wool waste or the like). The readings should be noted as soon as the thermometer ceases to rise.

§ 15.

With the exception of continuous-current field coils and all stationary windings, all parts of generators and motors shall be tested for temperature rise by means of the thermometer. In thermometric measurements the points of the highest temperature shall be measured in all cases as far as possible, and the results thus obtained shall be determinative.

§ 16.

The temperature rise of continuous-current field coils and all stationary windings of generators and motors shall be determined from their increase of resistance. In such cases, if the temperature coefficient of the copper be not particularly determined, it shall be taken as 0·004.

§ 17.

The temperature of transformer windings shall be determined from their increase of resistance. Regarding the temperature coefficient, see § 16.

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§ 18.

Under ordinary circumstances, and so long as the air temperature does not exceed 35° C., the temperature *rise*, measured in accordance with §§ 15 to 17, shall not *exceed* the following values :—

(*a*) On insulated windings and collector rings—	
With cotton insulation	50° C.
With cotton insulation under oil and paper insulation	60° C.
With enamel, mica, or asbestos insulation or preparations of these	80° C.

For stationary windings 10° C. higher values are permissible.

(*b*) On commutators	60° C.
(*c*) On the iron of generators and motors in which windings are embedded, the same values, according to insulation, as given under (*a*).	
(*d*) On bearings	50° C.

§ 19.

In tramway motors the temperature *rise* measured after 1 hour's continuous running at normal load in the test-room, in accordance with §§ 15 and 16, shall not *exceed* the following values :—

(*a*) On insulated windings and collector rings—	
With cotton insulation	70° C.
With paper insulation	80° C.
With enamel, mica, or asbestos insulation, or preparations of these...	100° C.

It is not permissible to exceed these limits in stationary windings.

(*b*) On commutators	80° C.
(*c*) On the iron, in which windings are embedded, the same values, according to insulation, as given under (*a*).	

§ 20.

For composite insulations the lower limiting value must be taken.

§ 21.

In continuously short-circuited windings the foregoing limiting values may be exceeded.

OVERLOADING.

§ 22.

Under service conditions machines and transformers should only be overloaded for so short a time, or to such an extent as regards

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heating, as to ensure that the permissible temperature rise does not become exceeded. On this account machines and transformers must be capable of carrying overloads within the following limits:—

Generators ... Motors ... ... Rotary Converters	25 per cent. for ½ hour, the power factor in alternating-current generators being taken as not less than the figure marked on the output-plate.
Motors ... ... Rotary Converters Transformers ...	40 per cent. for 3 minutes, the normal supply voltage in motors being maintained.

The commutators of continuous-current machines and rotary converters shall not be so affected by these tests that their behaviour on normal load will no longer meet the requirements of § 9.

With regard to mechanical soundness, machines intended to work at practically constant speed must withstand an increase in speed, running light, of about 15 per cent., unexcited and fully excited for a period of 5 minutes.

§ 23.

Generators must be capable of maintaining a constant voltage, running at constant speed, up to 15 per cent. overload, the power factor in alternating-current generators being taken as not less than the figure marked on the plate.

§ 24.

The tests of the mechanical and electrical overload capacity may be carried out irrespective of heating, and should therefore be commenced at such a temperature that the permissible temperature rise is not exceeded.

§ 25.

These regulations also hold good for generators with variable voltage, in which the voltage variation is practically proportional to the variation in speed. Generators and motors which work with a weakened field at normal voltage shall be examined by an overload test.

INSULATION.

§ 26.

The measurement of the insulation resistance is not essential, and in preference to this a test may be made of the soundness of the insulation ("piercing test") before it leaves the factory, and also before it is fixed in working position. Machines and transformers must accordingly be capable of withstanding a test of this kind with an increased pressure, according to the normal working pressure, as set forth below, for a period of 1 minute. This test shall be made when the machine is warm, and should only be repeated afterwards under exceptional circumstances, in order to avoid the danger of subsequent damage.

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Machines and transformers of pressures from 40 up to 5,000 volts shall be tested at two and a half times the working pressure, but in no case at less than 1,000 volts.

Machines and transformers of pressures from 5,000 up to 7,500 volts shall be tested at a pressure 7,500 volts in excess of the working pressure.

For pressures above 7,500 volts the test pressure shall be twice the working pressure.

Transformers for testing purposes are exempted from this.

Machines and transformers of pressures below 40 volts shall be tested at not less than 100 volts.

§ 27.

These test pressures apply to the insulation between the windings and the frame, as well as to the insulation between windings electrically separated from each other. In the latter case, if the windings are of different pressures, the test pressure specified for the higher shall always apply.

§ 28.

Two electrically connected windings of different pressures shall be tested likewise with the test pressure specified for the higher, between the windings and the frame.

§ 29.

When machines or transformers are connected in series without the above test, the windings which are joined together shall be tested to earth at a test pressure corresponding to the pressure of the complete group.

§ 30.

The above regulations regarding test pressures apply on the assumption that the test is undertaken with alternating current, the figures representing effective values. If the test is made with direct current the test pressures must be taken 1·4 times higher than those stated above.

§ 31.

If a winding is normally electrically connected to the frame the connection shall be broken during the insulation tests. The test pressure of such a winding to the frame is then determined in regard to the maximum pressure that can occur in service between any point of the winding and the frame.

§ 32.

For separately excited field-magnet coils the test pressure shall be three times the excitation voltage, but not less than 1,000 volts.

The windings of the rotors of asynchronous motors shall be tested at two and a half times the starting pressure, but not at less than 100 volts.

Short-circuited rotors do not require testing.

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§ 33.

Machines and transformers in operation should be able to stand an increase of pressure of about 30 per cent. for 5 minutes.

In machines this excess pressure test may be combined with a raising of the speed to about 15 per cent. above normal, provided, however, that the machine is not overloaded at the time.

These tests are merely intended to confirm the insulation soundness, and should be commenced at such a temperature of the machine that the permissible temperature rise is not exceeded.

EFFICIENCY.

§ 34.

The Efficiency is understood as the ratio of the power given out to the power supplied. It may be determined by the direct measurement of these two quantities, or indirectly by measuring the losses. The indirect methods are more easily carried out and less liable to errors of observation, and on this account preference is given to them in these Regulations.

In stating the efficiency the method by which it is intended to determine it, or by which it has been determined, shall be stated, a reference to the corresponding paragraph in these Regulations being sufficient.

In all cases the stated efficiency should represent that at the normal working temperature.

The efficiency shall be stated in regard to the method of working (see §§ 4, 5, and 6).

In alternating-current machines and transformers, when nothing to the contrary is agreed upon, the stated efficiency shall only be arrived at by means of a current supply in conjunction with an E.M.F. of approximately sine-wave form, and, so far as polyphase systems are concerned, only by means of symmetrical systems.

The efficiency without any special reference to load shall be regarded as that at normal load.

The power required for the field excitation and that absorbed in the field rheostat shall be taken into account as losses.

When artificial cooling is employed, in specifying the efficiency it shall be stated whether the power required for the means of cooling is to be taken into account as a loss. Failing any note to this effect, the efficiency shall be understood to include this loss.

§ 35.

For generators, synchronous motors, and transformers the efficiency shall be stated on the assumption that the current and voltage are in phase.

§ 36.

In machines with their own exciters the efficiencies of the two shall be stated independently.

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Methods of Determining Efficiency.

§ 37.

Direct Electrical Method.—This method can be applied to motor-generators, converters, and transformers, in which the power applied, as well as the power given out, can be determined entirely by electrical measurement. On account of the use of the same kind of measuring instruments, this method commends itself for the testing of similar machines or transformers.

§ 38.

Indirect Electrical Method.—Two machines of the same output, type, and current system being available at the same time, are so coupled, both mechanically and electrically, that one may run as a generator and the other as a motor. This combination is driven by a supply of current from an outside source in such a way that only the power required to make up the losses is drawn therefrom and measured. The running of the two machines is so regulated that the mean value of the power supplied to the motor and of that given out by the generator is as nearly as possible the same as the normal output of either machine independently. This mean value is determined by measurement. The power required for supplying the losses may also be obtained by mechanical means and measured electrically. In these measurements, if belt transmission cannot be avoided, the losses involved thereby must be taken into consideration accordingly.

The method described above is also applicable to transformers, provided that these are identical in regard to output, voltage, and frequency.

The losses occurring in any auxiliary apparatus must be taken into account.

§ 39.

Direct Brake Method.—This method is useful generally for small motors, but it can also be employed in the case of a small generator capable of running as a motor, provided that the conditions during the test are such that the magnetic and mechanical stresses, the speed, and the power differ as little as possible from the corresponding quantities when the machine operates as a generator.

§ 40.

Indirect Brake Method.—When a generator, or in like manner a motor, of the same power is available, the efficiency of which at different loads is accurately known, this may be used as a brake or as a driving motor correspondingly.

In the event of belt drive being employed in this method, the losses resulting therefrom must be taken into account.

§ 41.

Light-running Method.—The losses which occur in the working of a machine at normal speed and excitation are determined by running

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it as an unloaded motor. This brings out the losses due to windage, bearing and brush friction, hysteresis and eddy currents, in all of which the variations are independent of the load. The losses arising from heating with the increase of current, at the loads required, in the field and armature windings, brushes and contact resistance are determined by electrical measurements and by calculation, having regard to the motion and correct current value in the latter case, and to the heating of the machine in the former case. In asynchronous motors the losses in the rotor may be determined by measurement of the slip instead of by measurement of the resistance. Any possible loss occurring in the field rheostat in normal running must be considered in the calculations. This method may be applied in like manner to transformers.

The sum of the above-mentioned losses may be designated as "the measurable loss."

The efficiency is then given by the ratio of the output to the output plus "the measurable loss."

§ 42.

Auxiliary Motor Method.—If the direct determination of the losses due to windage, bearing and brush friction, and also hysteresis and eddy currents presents difficulties in certain cases, or if a current supply similar to that required for the machine under test is not available, the losses for windage and bearing friction, as well as for hysteresis and eddy currents, may be determined by employing an auxiliary motor.

The determination of these losses in the machine under test is then made by ascertaining the power supplied to the driving motor at normal excitation of the machine under test and subtracting therefrom the losses of the auxiliary motor, and in the event of a belt drive, the losses due to this also.

The losses in the auxiliary motor are determined by running the motor unloaded at the same speed and voltage as during the main test, and by electrical measurements to ascertain the losses in the field and armature windings, the brushes and contact resistance at the required load, in accordance with § 41. For the rest, as regards the machine under test, this is treated just as in § 41, and the efficiency is defined in the same way.

A steam engine driving the machine can also be employed as an auxiliary motor provided that it is capable of being uncoupled. In this case the determination is made by first indicating the engine with the unloaded generator at normal speed and excitation, and again afterwards when the generator is disconnected from the engine. The difference in power represents the no-load losses for windage, bearing and brush friction, hysteresis and eddy currents, after taking into account any possible excitation produced at the same time by the steam engine. On account of the inaccuracy attaching to the light-load indicator diagrams this method must be employed with special caution.

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§ 43.

Indicator Method.—If a generator is direct driven by a steam engine from which it cannot be disconnected, the efficiency may be determined exclusive of friction losses. The no-load losses due to hysteresis and eddy currents at normal speed and terminal voltage are determined by means of indicator diagrams, the engine being indicated both with and without the field excitation. When the exciter is driven by the same steam engine the power required for this must be deducted. The difference remaining is considered as the loss due to hysteresis and eddy currents, the variations in which are independent of the load. The losses due to heating in the field and armature windings, brushes, and contact resistance are determined by electrical measurements and by calculation, having regard to the motion and correct current value in the latter case, and to the heating of the machine in the former case. Any possible loss in the field rheostat at normal load must be taken into account. The sum of the above-mentioned losses may be designated as "the measurable loss." The efficiency is then given by the ratio of the output to the sum of the output and "the measurable loss."

§ 44.

Separation Method.—In machines which can only be run by using bearings not belonging to them the efficiency, neglecting friction, is determined in the following manner: The hysteresis and eddy-current losses are determined electrically by testing the machine as an unloaded motor in a similar manner to that used in the "light-running method." In order to separate the windage and bearing and brush friction losses from the hysteresis and eddy-current losses proceed as follows: The machine must be tested at several different voltages at the normal speed, bringing the voltage down as low as possible; having taken, of course, an observation at normal voltage, and also, if possible, one at 25 per cent. higher voltage. The values obtained are plotted graphically, and by producing backwards the resultant curve the losses which would occur at zero voltage may be ascertained. This value represents the friction loss, and is deducted from the observed no-load loss at normal voltage. The difference then gives the hysteresis and eddy-current losses, the variations in which do not depend on the load. The remaining losses are measured according to § 41. The sum of the hysteresis and eddy-current losses, as well as the losses due to heating of the field and armature windings, the brushes and contact resistance, for the loaded machine may be designated as "the measurable loss," and the efficiency is taken as the ratio of the output to the sum of the output plus the "measurable loss."

The determination of the hysteresis and eddy-current losses can also be made by means of an auxiliary motor.

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Voltage Regulation.

§ 45.

The voltage regulation in alternating-current generators is understood as the variation in the voltage which occurs when the maximum current in the armature, as given on the output plate, is switched off on the normal voltage at the terminals, the speed and excitation being unaltered.

§ 46.

In machines which are only intended for a non-inductive load it is sufficient to state the voltage regulation for this case. In machines intended for inductive loads, however, it is necessary to state the voltage regulation for a non-inductive load and also the regulation for an inductive load at 0·8 power factor.

It is, of course, also permissible to give the voltage regulation for any other power factor.

§ 47.

In testing the voltage regulation of continuous-current machines the following method may be applied: Continuous-current machines with shunt excitation, with compound excitation, or with separate excitation are tested, without adjustment of the excitation, at not less than four approximately equal steps in the load, from full load at normal voltage down to no load at constant normal speed. The difference between the highest and the lowest observed voltages gives the voltage regulation. The brushes must not be moved during this test.

§ 48.

In transformers the ohmic voltage drop, as well as the short-circuit voltage, at the normal current shall be stated, in each case with reference to the secondary windings.

It is permissible to measure the short-circuit voltage at a current value not greatly differing from the normal value, and to calculate for this proportionally.

APPENDIX.

It is recommended that in new schemes and for price lists the following values be adopted, as far as possible, for the frequency, speed, and voltage.

The frequency should be either 25 or 50 cycles.

The speeds of alternating-current and 3-phase-current machines should be gradated in accordance with the following table:—

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Number of Poles.	Speed of Generator, Synchronous Motor, or Unloaded Asynchronous Motor at Frequency of—		Number of Poles.	Speed of Generator, Synchronous Motor or Unloaded Asynchronous Motor at Frequency of—	
	25 ∿.	50 ∿		25 ∿.	50 ∿.
2	1,500·0	3,000	28	107	214·0
4	750·0	1,500	32	94	187·5
6	500 0	1,000	36	83	166·0
8	375·0	750	40	75	150·0
10	300·0	600	48	—	125·0
12	250·0	500	56	—	107·0
16	187·5	375	64	—	94·0
20	150·0	300	72	—	83·0
24	125·0	250	80	—	75·0

The voltage should be determined from the following tables :—

(*a*) *Continuous Current.*

Motor.	Generator.
110 volts.	115 volts.
220 „	230 „
440 „	470 „
500 „	550 „

(*b*) *Alternating Current.*

Motor, or at Primary Terminals of Transformer.	Generator, or at Secondary Terminals of Transformer.
110 volts.	115 volts.
220 „	230 „
500 „	525 „
1,000 „	1,050 „
2,000 „	2,100 „
3,000 „	3,150 „
5,000 „	5,250 „

REGULATIONS REGARDING THE CONNECTION OF MOTORS TO A PUBLIC SUPPLY.

§ 1.

General.

(*a*) The motors must conform to the "Standard Regulations for the Rating and Testing of Electrical Machines and Transformers" of the Society of German Electrical Engineers.

(*b*) In addition to the statements on the output-plate made in accordance with § 2 of the "Regulations" referred to above, the power factor ($\cos\phi$) of single-phase or polyphase motors must also be marked on the plate.

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§ 2.

NOTIFICATION.

(*a*) The Supply Works must be notified of all motors, giving their predetermined output and the method of working (see § 7 of the "Machine" Regulations), which statements must agree with the corresponding statements on the output-plate.

(*b*) In every notification of a motor the purpose for which it is to be used shall be stated, and particularly whether the motor will be required for a "low" or for a "high" starting power; further, in continuous-current motors of over 1 H.P. and in single-phase and polyphase motors of over 2 H.P., whether the motor is intended for a "low" or for a "high" starting current.

§ 3.

STARTING CURRENT OF CONTINUOUS-CURRENT MOTORS.

The current taken from the supply system for the starting of motors under ordinary conditions shall not exceed the following values :—

For Motors of—	Watts per Horse-power.	
From 0·5 up to 1 H.P.	3,500	for "low" starting power.
„ 1 „ 2 „	1,500	
„ 2 „ 15 „	1,250	
„ 15 H.P. upwards	1,000	
„ 1 up to 15 H.P.	2,500	for "high" starting power.
„ 15 H.P. upwards	2,000	

Note.—With the starting current allowed for the "low" starting power, as a rule the normal turning moment may be obtained in motors of from 1 up to 15 H.P., and three-quarters of the normal turning moment in motors of over 15 H.P. With the starting current allowed for the "high" starting power, as a rule twice the normal turning moment may be obtained.

§ 4.

STARTING CURRENT OF POLYPHASE MOTORS.

(*a*) The current taken from the supply system for the starting of motors under ordinary conditions shall not exceed the following values :—

For Motors of—	Volt-amperes per Horse-power.	
From 0·5 up to 1 H.P.	3,500	
„ 1 „ 1·5 „	3,000	
„ 1·5 „ 2 „	2,500	
„ 2 „ 5 „	1,600	for "low" starting power.
„ 5 „ 15 „	1,400	
„ 15 H.P. upwards	1,000	
„ 2 up to 5 H.P.	3,200	for "high" starting power.
„ 5 „ 15 „	2,900	
„ 15 H.P. upwards	2,500	

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(*b*) The quantity "volt-amperes" is understood as the product of the current, the working pressure, and the phase multiplying factor.

Note.—With the starting current allowed for the "low" starting power, as a rule the normal turning moment may be obtained in motors of from 2 up to 15 H.P., and three-quarters of the normal turning moment in motors of over 15 H.P. With the starting current allowed for the "high" starting power, as a rule twice the normal turning moment may be obtained.

§ 5.

STARTING CURRENT OF SINGLE-PHASE MOTORS.

(*a*) The current taken from the supply system for the starting of motors under ordinary conditions shall not exceed the following values :—

For Motors of—	Volt-amperes per Horse-power.	
From 0·5 up to 1 H.P.	3,500	
„ 1 „ 1·5 „	3,250	
„ 1·5 „ 2 „	3,000	
„ 2 „ 5 „	2,000	
„ 5 „ 15 „	1,500	for "low" starting power.
„ 15 H.P. upwards	1,250	
„ 2 up to 5 H.P.	3,500	
„ 5 „ 15 „	3,000	for "high" starting power.
„ 15 H.P. upwards	2,500	

(*b*) The quantity "volt-amperes" is understood as the product of the current and the working pressure.

Note.—With the starting current allowed for the "low" starting power, as a rule one-quarter of the normal turning moment may be obtained in ordinary induction motors, and the normal turning moment in commutator motors. With the starting current allowed for the "high" starting power, as a rule two-thirds of the normal turning moment may be obtained in ordinary induction motors, and twice the normal turning moment in commutator motors.

§ 6.

POWER FACTOR OF POLYPHASE MOTORS.

The value of the power factor ($\cos\phi$) at full load shall be not less than—

0·60	for motors up to and including			0·5	H.P.
0·65	„	„	„	1	„
0·70	„	„	„	1·5	„
0·75	„	„	„	5	„
0·77	„	„	„	10	„
0·80	„	„	„	15	„
0·82	„	„	„	20	„
0·85	„	of over 20 H.P.			

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§ 7.

Power Factor of Single-phase Motors.

The value of the power factor ($\cos \phi$) at full load shall be not less than—

0·60	for motors up to and including			0·5	H.P.
0·65	„	„	„	1	„
0·70	„	„	„	1·5	„
0·73	„	„	„	5	„
0·75	„	„	„	10	„
0·77	„	„	„	15	„
0·80	„	„	„	20	„
0·82	„	of over 20 H.P.			

§ 8.

Carrying Out of the Measurements.

(*a*) For measuring the starting current a special ammeter with an adjustable pointer is recommended. The pointer should be moved forward to a position on the scale about 5 per cent. below the current value to be measured. Hot-wire instruments must not be used for this purpose.

(*b*) The measurement of the power factor is effected by taking simultaneous readings of the amperes, volts, and watts when running at the normal current value stated on the output-plate.

(*c*) The measurements shall be made at the normal voltage, though a drop of not more than 5 per cent. is permissible.

§ 9.

Special Motors.

The connection of motors which for technical reasons are prevented from conforming to the above Regulations, for example, as regards power factor on account of low speed, or as regards starting current on account of unusually high starting torque, and so on, is subject to special agreement between the parties concerned.

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RULES FOR CONTINUOUS-CURRENT TRACTION MOTORS.

ADOPTED BY THE INTERNATIONAL CONGRESS FOR TRAMWAYS AND LIGHT RAILWAYS, MILAN, 1906.

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General Rule.

1. The following Rules shall be observed in offers of sale and in the actual execution of orders unless they shall have been previously modified by mutual agreement between the seller and the buyer.

Definitions.

2. *Power.*—The mechanical power developed by a motor, or simply the power of a motor is the power developed on the axle of the car under the conditions set out below.*

The permanent power of a motor is the power which, with current at the normal pressure of supply, can be developed by the motor during ten consecutive hours without there being undue heating in the sense indicated in Rule 6.

The normal power of a motor shall mean the power which, with current at the normal pressure of supply, can be developed by the motor uninterruptedly during one hour without there being undue heating in the sense indicated in the Rule for heating (see section 6).

The maximum power of a motor is the power which, with current at the normal pressure of supply, can be developed by the motor during five consecutive minutes with practically sparkless commutation.

3. *Tractive Effort.*—The tractive effort of a motor is the tangential force developed by the motor under the conditions of the Rule relating to "Acceptance Test," with its proper gearing at the circumference of a wheel of the diameter specified for the car-wheels.†

4. *Speed.*—Speed shall mean the speed of the rim of the car-wheels.

5. *Efficiency.*—Efficiency shall mean the ratio of the mechanical power developed on the car axle to the electrical power supplied to the motor terminals at the normal pressure of the supply.

6. *Heating.*—The heating of a motor shall be deemed to be excessive when, with the initial temperature of the surrounding air at 25° C. (77° F.), the motor reaches, after 10 hours' running at permanent power,

* In certain special cases it may be useful to determine the intrinsic power of the motor, excluding the means of transmission (gears, axles, etc.). The word "intrinsic" will in such cases be added to each of the categories of power defined in the Rule relating to power.

† In the case of gearless motors the intrinsic tractive effort shall be the tangential force exerted at the circumference of a wheel 50 cm, in radius fixed to the armature shaft.

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or after 1 hour's running at normal power, a final temperature exceeding that of the surrounding air by the following values :—

(*a*) Windings with—	
Cotton insulation	70° C. (126° F.)
Paper insulation	80° C. (144° F.)
Insulation by mica, asbestos, or other substances possessing the same insulating and fire-resisting properties	100° C. (180° F.)
(*b*) Commutators	80° C. (144° F.)
(*c*) For any metal portions in which the windings are embedded, the value corresponding to that given for the windings, according to the kind of insulation used for the latter.	

When the windings have more than one insulating material, the lower limit is to be taken.

In cases where the temperature of the testing-room * is less or greater than 25° C. (77° F.), the values given above must be increased or decreased by the difference.

Data.

7. In addition to the normal pressure of supply, the specifications shall contain the following data, worked out in relation to the normal pressure of supply :—

(1) The permanent power of the motor and the corresponding current.
(2) The normal power of the motor and the corresponding current.
(3) The maximum power of the motor and the corresponding current.
(4) The efficiency at permanent power and at normal power, the temperature of the motor being taken as 75° C. (167° F.).
(5) The insulating materials used.
(6) The overall dimensions of the motor.

There shall also be specified the gear ratio for a given diameter of the car-wheels, the tractive effort, and the speed for the permanent, normal, and maximum powers. A curve shall be supplied showing the tractive effort, speed, and efficiency as functions of the current.†

Rating Plate.

8. Besides the foregoing particulars contained in the specification, there must be given on a rating plate fixed to each motor the normal pressure of the supply, the normal power, the corresponding number of revolutions per minnte, and the corresponding current.

* Note added by the translator : The term "testing-room" is probably a misprint for "space in which the motor will be used."

† At the request of the purchaser, the seller shall for definite working conditions supply curves showing the time-rate of heating and cooling of the motor.

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Construction.

9. The field frame shall be of the shell type, so constructed as to prevent external magnetic leakage. The shell must be completely proof against the entry of dust and splashed water.

Hermetically closed inspection doors must be provided for the purpose of brush maintenance.

By brush maintenance is to be understood not only the changing of the brushes, but also of the brush-holders.

10. The bearings shall be so constructed that the lubricating oil cannot reach the interior of the motor.

11. The motor, and particularly the commutator and brushes, shall be so constructed that for a fixed brush position, with the motor revolving either way, there shall be practically no sparking for any load within the limit of the maximum power.

12. The insulation of the windings from the magnet frame and armature core shall be such that, in the event of the motor attaining the highest permissible temperature, it will withstand for the next 5 minutes an alternating pressure of four times the normal pressure of the supply.

13. All the parts of the motor intended to be periodically replaced, particularly the armature, the field windings, the former-wound armature coils, the commutators, etc., shall be completely interchangeable—that is, they shall fit into their places without requiring any further adjustment—the armatures, particularly, shall be capable of replacement without the brush-holders having to be taken off or shifted.

Acceptance Test.

14. Motors will be tested for approval before they are fitted to the cars, both with a view of examining the workmanship and construction, and also of ascertaining their power, tractive effort, speed, efficiency, and heating.

A. *Determination of the Mechanical Power.*

15. For testing the power a dynamo-metric brake may be used or a dynamo machine, the armature of which is coupled direct to the car axle, providing its efficiency is accurately known. It is not permissible to connect the armature of the power-absorbing dynamo machine to the car axle by gearing.

B. *Rating of Motors by the Measurement of their Temperature Rise.*

16. The power of motors will be rated, according to definition, by their rise of temperature.

17. For testing temperature rise, no removal, opening, or material alteration of covering plates, caps, etc., required for the normal working of the motors, may be made ; neither may any artificial means be used to imitate during the test the air current produced in working conditions by the motion of the car.

18. By the term "air temperature" is to be understood the temperature of the air flowing naturally towards the motor, and if no such current can be found, the mean temperature of the air round the motor

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shall be taken at the height of its centre, and in both cases at a distance of about 1 metre from the machine. The air temperature shall be taken at intervals during the last quarter of the time of test, and the mean value of these readings shall be considered to be the air temperature.

19. If a thermometer be employed to measure temperatures, the best possible conduction of heat shall be secured between the thermometer bulb and the part of the motor whose temperature is to be taken —for instance, by means of a wrapping of tinfoil. In order to prevent dissipation of heat, the bulb and place of contact shall be covered with some bad conductor of heat, such as dry woollen waste.

The reading of the thermometer shall not be taken until it has ceased to rise.

20. Except in the windings, all parts of the motor shall be tested for rise of temperature by means of a thermometer.

As far as possible, the hottest points shall be determined, in order to arrive at the true heating effect.

21. The temperature of the windings shall be determined by resistance measurements.

If the temperature coefficient of the copper is not already known, it shall be taken as 0·004.

C. *Measurement of the Efficiency of Motors.*

22. To determine the efficiency of a motor by itself, or with its gearing, the brake method may be employed, the brake being keyed in the first case to the motor shaft, and in the second case to a separate axle to represent that of the car.

With proper precautions it is also permissible to use the purely electrical method indicated in the following paragraphs.

23. The combined efficiency of motor and gear may be determined practically by the following method *:—

Two of the motors to be tested shall be coupled mechanically to an auxiliary shaft by gearing similar to that which will be fitted to the car axle.

One of the motors shall work as a motor and the other as a generator, the two being electrically so coupled as to require from an outside source only the power P necessary to cover the losses. If P_1 be the total power supplied to the motor, and P_2 the total power developed by the generator, we have $P = P_1 - P_2$, and the efficiency of one motor with its gear will be $\eta = \sqrt{\frac{P_2}{P_1}}$.

The powers P_1 and P_2 shall be measured electrically.

As a check, it is advisable also to measure the externally supplied power P.

24. When it is required to determine the efficiency of motors intended to be fitted direct to the car axles, the preceding methods may still be applied; it will be sufficient in this case to couple directly the armatures of the two motors.

* This method is not theoretically accurate, on account of the difference in the mode of working between the driving and driven system; the amount of error thus introduced is, however, within permissible limits if the gear ratio is not high.

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ORIGINAL COMMUNICATION.

THE METAL TUNGSTEN AS "VALVE' ELECTRODE.

By L. H. WALTER, M.A., Associate Member.

(*Received July* 13, 1909.)

CONTENTS.

Introduction.
Tungsten as "Valve" Anode.
Experiments with Direct Current.
Experiments with Alternating Current.
Summary of Results.

INTRODUCTION.

The number of metals which show the effect known as "valve action" when used as electrodes in electrolytic cells has of recent years been considerably increased; and owing mainly to the thorough and systematic investigations of G. Schultze,* a somewhat better understanding as to the phenomena involved has been arrived at.

From the two first known, aluminium and magnesium, the list has been extended until it now definitely includes quite a large number of metals. If, however, these are classified as belonging either (1) to those showing the more general behaviour—which consists in the cell developing a film offering a very high resistance to a direct current passing through it in the direction in which the metal functions as anode, and a comparatively negligible resistance in the reverse direction—or (2) to those that show the less general phenomenon, in which a similar high resistance is offered, due to a film which forms under alternating current even, during the phase which is anodic so far as the valve metal is concerned, there remain but two additional metals, viz., tantalum and niobium, which, as recent work has shown, can be classed with the original two as manifesting the true rectifying effect.

TUNGSTEN AS "VALVE" ANODE.

The author has now found that yet another metal, hitherto untried, gives the valve effect in a very pronounced manner; in addition, this metal, tungsten, "forms" under alternating current. In this preliminary paper it is proposed to give a brief account of some experiments

* *Zeitschrift für Electrochemie*, vol. 14, p. 333, 1908.

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which have been made in consequence of this discovery, although the complete results of a further investigation which is now in progress are reserved for a later communication.

The effect was first observed when making experiments with a sealed-in tungsten lamp filament used as anode in a form of electrolytic detector with sodium chloride solution as electrolyte. In the course of this work it was noticed that on raising and still further raising the polarising potential difference, the characteristic "boiling" or hissing of the detector, due to evolution of gases, was entirely absent; and when it was found that 8 volts could be applied directly across the electrodes without the least "boiling" in the telephone, the similarity in the behaviour to that of the tantalum point-electrode suggested that there must exist, in this case also, a marked asymmetric effect.

Experiments with Direct Current.

Experiments with a somewhat larger anode, consisting of a non-sheathed length of an inch or so of the filament from a 50-c.p. osram lamp, with dilute sulphuric acid as electrolyte and applied voltages up to 45 volts, showed that the phenomenon was not merely an asymmetric effect due to the difference in the areas of the electrodes as in Holtz's * asymmetric cells, but was apparently a real "valve" effect.

The investigation was continued and extended to higher voltages, several other electrolytes being tried. The maximum pressure obtainable at the time being 90 volts, it was found that this voltage could be withstood by the tungsten anode in sulphuric acid of 1 : 15 concentration (15), in potassium iodide (0·2), acetic acid (0·1), potassium bichromate (1·8), sodium potassium tartrate (0·1), and borax (1·0) solutions, none very dilute. The residual current through the cell in milliamperes after 10 seconds is shown by the figures within brackets, the area of immersed anode being 0·034 square centimetre approximately.

For the purpose of these experiments it was found convenient to embed the end of the filament in a plug of Wood's fusible alloy which itself formed a stopper at the top of a perforated ebonite tube that served to protect the very delicate filament from injury.

The behaviour of tungsten in sulphuric acid of considerable strength with an applied potential difference of 90 volts is of special interest, in that, were it possible to make use of this electrolyte in rectifiers with tungsten anodes, the dimensions of the cells would be able to be much reduced as compared with those of the cells usually employed, since the conductivity of the acid is so high. For this reason, although it appears probable that, as in the case of other metals, *e.g.*, aluminium, tantalum, the critical voltage is notably higher in other, less active electrolytes, the first experiments were confined to the examination of the behaviour with sulphuric acid and with potassium bichromate. These are also good tests for the aluminium and tantalum: Schulze gives for the critical voltages of these two metals 45 and 190 volts respectively

* *Physikalische Zeitschrift*, vol. 6, p. 480, 1905.

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TABLE I.

Milliamperes through Cell in Effective Direction.

Potential Difference across Cell (Volts).	In Sulphuric Acid.			In Potassium Bichromate.		
	Tungsten.	Tantalum.	Aluminium.	Tungsten.	Tantalum.	Aluminium.
10	< 0·02	—	—	—	—	—
20	< 0·02	0·10	—	—	—	0·20
30	< 0·02	—	—	—	—	—
40	0·02	0·10	0·12	0·025	0·10	0·30
50	0·03	—	0·20	—	—	—
55	—	—	0·55	—	—	—
66	0·05	0·15	—	0·03	0·15	—
70	0·10	—	—	—	—	—
80	0·20	—	—	0·05	—	—
90	1·00 (jerky)	—	—	0·13	—	—
100	(sparked at 94 volts)	0·20	—	0·13	0·20	0·40
105	—	—	—	2·0 (jerky)	—	—
120	—	—	—	—	0·30	—
150	—	0·50	—	—	0·30	—
160	—	—	—	—	—	—
180	—	—	—	—	0·50	—
200	—	—	—	—	1·70	—

Tungsten Anode in

	Nitric Acid.	Hydrochloric Acid.	Potassium Sulphate.	Potassium Chloride.
10	0·04	0·13	0·10	—
20	0·05	0·15	0·13	0·02
30	0·10	0·20	0·20	0·04
40	0·13	0·25	0·25	0·13
50	0·15	0·30	0·25	0·17
60	0·15	0·30	0·30	0·20
70	0·15	0·50 (jerky)	0·30	0·22
80	0·25 (jerky)	—	0·35	2·0
90	0·50 (jerky)	—	9·0	6·0 (jerky)
94	—	—	12·0	20·0 (jerky)
100	—	—	—	—

in sulphuric acid and 95 and 70 volts in potassium bichromate. A few other electrolytes of high conductivity were also tried, including hydrochloric and nitric acids.

Owing to the fact that tungsten is at present only obtainable in

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the form of lamp filaments, the anode used is necessarily of very small dimensions and surface, and hence, with a view to eliminating any differences which might be due to the unequal size of the electrodes, two test cells were made up having anodes, of aluminium and tantalum respectively, of such dimensions as to offer a surface of the same order to the electrolyte, approximately 0·1, 0·15, 0·4 square centimetre in the case of tungsten, aluminium, and tantalum respectively. The lead kathodes had a surface of about 30 square centimetres, the circular containing cell measuring 3 in. high by 1½ in. diameter. With such a cell a current up to 0·5 ampere could safely be passed in the non-effective direction for short periods, the ohmic resistance being about 6 ohms. The sulphuric acid used was battery acid of density 1·200, while the potassium bichromate was approximately a 5 per cent.

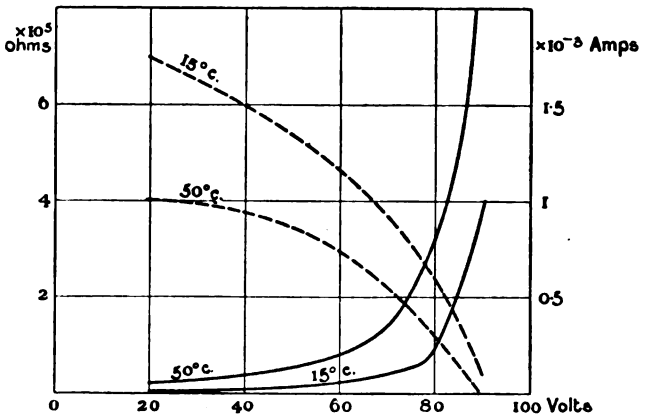

FIG. 1.

solution. The valve electrode was simply dipped into the electrolyte from above.

While such high limiting voltages may not be reached in this way as with Schultze's arrangement, the obtaining of very high critical voltages possesses only a theoretical interest, since the cell is of little practical use anywhere near the breakdown voltage.

A difficulty arises as to the representation of the results: Schultze gives curves showing the critical voltage plotted against time in minutes as abscissa. In the present case, for showing the scaling-off property of the anode, the residual current through the cell, in milliamperes after 20 seconds, is plotted as ordinate against the potential difference across the cell as abscissa.

Besides the critical voltage there are two other factors which determine the suitability or unsuitability of a valve electrode: the effect of higher temperatures upon the cell, and the effect of cutting off the current. As regards the former, the effect of the temperature

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of the electrolyte upon the leakage current in sulphuric acid is shown in Fig. 1. The full curves give the normal current at 15° and at 50° C. respectively, the dotted curves the respective resistances. These latter indicate very clearly where the critical voltage must lie (zero resistance) without it being necessary to actually break down the film. The usual behaviour, namely, that the leakage current is greater at higher temperatures, is observed, but the critical voltage is very little altered.

The effect of cutting off the current for shorter or longer periods can be seen in Fig. 2 for three different applied voltages, viz., 25, 50 and 75 volts, also in sulphuric acid. The points of the full-line curves which lie on the vertical axis show the normal resistances of the cell;

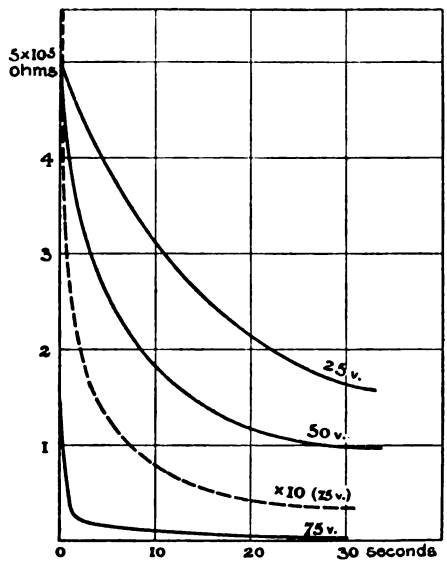

FIG. 2.

the other points give the resistances plotted from the currents observed on remaking the circuit after the current has been cut off for times up to half a minute.

At 25 and up to 50 volts it will be seen that the decrease of resistance of the anode film, though fairly rapid, is of a different order to that which occurs at 75 volts. It is interesting to observe that if the curve for 75 volts is reproduced with ordinates all multiplied by ten, the curve so obtained (dotted curve of Fig. 2) is very similar in shape to those for the lower voltages.

EXPERIMENTS WITH ALTERNATING CURRENT.

But few experiments have as yet been made with the cell on alternating current.

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The first trials with an arrangement of three cells having together four anodes, which served as a bridge, showed that, using new tungsten anodes which had never previously been formed, a direct current was at once obtained on switching on the alternating supply, the applied voltage being 25 volts and the rectified current, which was passed through three accumulator cells, being 0·25 ampere. With a voltage of 25 at the direct-current (rectified) terminals and 0·043 ampere on a moving coil instrument in the same circuit the reading of a hot-wire ammeter in the alternate-current circuit was 0·13 ampere (anodic current density > 4 amperes /cm.^{2}), hence the current transformation ratio as defined by Jakob,* was about 33 per cent.; this being, however, only about 1 minute after closing the circuit.

The difficulty here was that currents smaller than 0·1 ampere were not readable on the ammeter which was available. This current could be exceeded for short intervals, but owing to the small anode surface and the consequent high current density, the heating was so great that the efficiency rapidly fell off. Now that thicker filaments are promised in the near future it is hoped to obtain results for longer periods.

In conclusion it may be stated that, although the tungsten used is chemically metal, it can hardly be looked upon as being physically in the metallic (massive) state. Tungsten having been shown to behave chemically quite differently according as it is in the fused or reguline condition, or in the state of powder—notably in the greater indifference to acids shown by the fused form—it appears probable that the metal will make a more favourable showing when it is obtainable in the drawn condition, which has already been shown to be realisable, by previously alloying with nickel.

Summary of Results.

It is here shown that the metal tungsten, like aluminium and tantalum, behaves as a valve electrode in a large number of electrolytes, those which have been tried being for the most part of high conductivity and less adapted to the securing merely of high critical voltages. The critical voltages in the strong acids are as a rule higher with tungsten than with aluminium, but not so high as with tantalum.

The sensitiveness to heating is not at all pronounced. The sensitiveness to cutting off of the current appears, on the other hand, to be very great indeed. The great activity and considerable concentration of the electrolyte used must, however, be borne in mind.

The author's thanks are due to Mr. S. Skinner, M.A., for placing the laboratories of the South Western Polytechnic Institute at his disposal for the later experiments.

* *Sammlung Elektrotechnische Vorträge*, 9, p. 76, 1906.

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ORIGINAL COMMUNICATION.

ON MAGNETIC TESTING OF IRON WITH ALTERNATING CURRENT.

By ALBERT CAMPBELL, B.A., Associate Member.

(From the National Physical Laboratory.)

(*Received June* 23, 1909.)

§ 1. Preliminary.
§ 2. Influence of Form Factor.
§ 3. Method of Test.
§ 4. Typical Results.
§ 5. Effect of Thickness of Sheets.
§ 6. Proper Dimensions of Ring Stampings.

§ 1. PRELIMINARY.

The introduction of high resistivity iron alloys with low hysteresis loss has made it more than ever desirable that sheet material for use in transformers, or other alternating machinery, should be tested for hysteresis and eddy current loss by means of actual alternating current. The object of the present paper is to describe the method by which these tests are carried out at the National Physical Laboratory, and to include some of the more interesting results obtained during the past year. Before describing our own work, however, brief reference must be made to that of earlier experimenters. The subject has been investigated by a number of persons in this country, the Continent, and America, but I may single out, as being of fundamental importance, the work of G. Roessler,* as he was the first to point out the influence of the form factor of the alternating voltage used. This theory forms the basis of the thorough investigations made by Gumlich and Rose,† and in what follows I have made considerable use of their clear treatment of the subject. While our experiments were in progress, a paper appeared by Lloyd and Fisher,‡ describing the

* *Verband Deutscher Elektrotechniker*, July 9, 1895. (*Electrician*, vol. 36, p. 124, 1895.) Almost immediately his results were independently established by the experiments of Beeton, Taylor, and Barr (*Journal of the Institution of Electrical Engineers*, vol. 25, p. 474, 1896).

† *Elektrotechnische Zeitschrift*, vol. 26, p. 403 and p. 503, 1905.

‡ *Bulletin Bureau of Standards*, vol. 4, p. 467, 1908.

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method of test employed at the Bureau of Standards, Washington; their method is very similar to that used by us, and is thoroughly discussed in their paper; and, lastly, an interesting paper has appeared by Lloyd* on the "Dependence of Magnetic Hysteresis on Wave Form."

§ 2. Influence of Form Factor.

When an iron ring is magnetised by an alternating current of frequency $n \sim$ per second, the eddy current losses in the iron not only depend on n and the flux density, but also on the form factor f of the induced secondary voltage, where f is equal to V/v_{mean}, v_{mean} being the mean value of the induced voltage without regard to sign, and V the effective value of the same. According to Roessler, at constant temperature the iron losses in watts per cubic centimetre due to hysteresis and eddy currents respectively are given by the two terms of the expression—

$$10^{-7}(\eta\, n\, B_{max.}^{1.6} + \xi\, n^2 f^2 B_{max.}^2) \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where—

$B_{max.}$ = maximum value of the flux density,

η = Steinmetz's coefficient,

and—

ξ = eddy current coefficient.

If w = watts per kilogram at frequency n, we have—

$$w = \frac{10^{-7}}{D}(\eta\, n\, B_{max.}^{1.6} + \xi\, n^2 f^2 B_{max.}^2) \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where—

D = density of the iron.

The main object of the investigations here described was to test the accuracy of this formula for various materials and widely different values of the form factor f†—*i.e.*, for widely different wave-forms. As will be seen below, this led to a convenient method of separating the hysteresis and eddy current losses. It is usual to take 50 $\sim$ per second as standard frequency, and $B_{max.} = 10{,}000$ as standard flux density. Most of our results were obtained with frequencies quite near 50 $\sim$ per second, and all of them were reduced to the standard, the watts per kilogram being $50\, w/n$. Except where otherwise mentioned, observations were always made with $B_{max.}$ exactly 10,000.

§ 3. Method of Test.

All the specimens were in the form of rings, usually of inner and outer diameters, 12 and 15 cm. respectively; these were built up of stampings with paper insulation between them, and each was wound with at least two secondary coils of 10 and 30 turns respectively, and

* *Bulletin Bureau of Standards*, vol. 5, p. 381, 1909.

† Gumlich has found it true with certain samples for small variation of f, and also for a considerable range of frequency. It is clear that it cannot be true for very high frequencies.

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sometimes one of 100 turns was added. The primary windings were 30 or 100 turns. All the windings were evenly distributed over the ring. The method of test consisted in the determination of the $B_{max.}$ and the form factor of the induced voltage by the help of a commutator as used by Sahulka* and Townsend,† while the corresponding power lost was measured by a sensitive wattmeter whose shunt circuit was connected to one of the secondary windings of the ring after the method of Steinmetz.‡ The connections are shown in Fig. 1.

An alternator or rotary converter A, working through the transformer M, supplies current to the primary of the ring D, the frequency being measured by the Campbell frequency teller F. The primary current passes through the series coils of the wattmeter H, and the shunt circuit of the wattmeter is connected through a high resistance

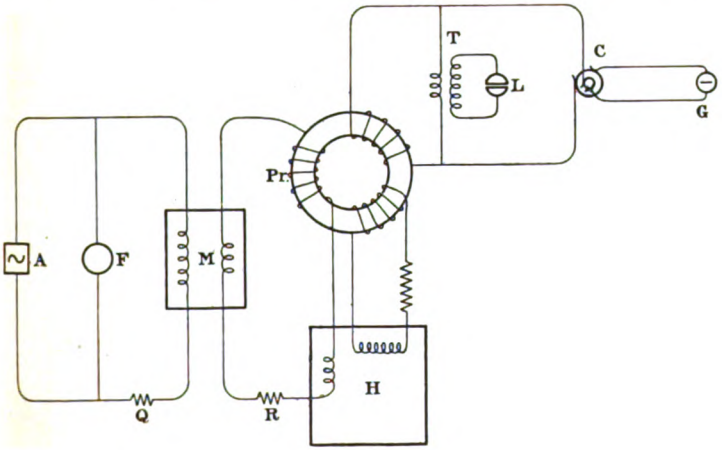

FIG. 1.

to the secondary winding S. Another secondary coil Z (of 10 turns) is connected through the high ratio transformer T to the 100-volt electrostatic voltmeter L, and also through the commutator C to the galvanometer G, which, by the addition of suitable high resistance, is arranged to read voltage directly. The commutator is run by a synchronous motor supplied with current from the alternator A; it reverses the connections to the galvanometer circuit twice per period, and when, by shifting round a pair of movable brushes on C, the phase of the reversals is set to give a maximum reading on the galvanometer, this reading will measure v_{mean}, the mean value of the voltage induced in the winding Z.§

* *Zeitschrift für Elektrotechnik*, vol. 16, p. 4, 1898.

† *American Institute Electrical Engineers, Transactions*, vol. 17, p. 5, 1900.

‡ Ibid., vol. 9, p. 624, 1892. The method seems to have been used first in this country by L. W. Wild (*Electrician*, vol. 54, p. 128, 1904).

§ See J. Sahulka (*loc. cit.*), also T. Lyle (*Philosophical Magazine*, vol. 6, p. 549, 1903, and vol. 9, p. 102, 1905).

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The reading of the voltmeter L multiplied by the transformation ratio of T gives V, the effective voltage induced in Z, and hence f, the form factor (which is equal to V/v_{mean}) is immediately found. The galvanometer reading also gives B in the ring since—

$$B_{max.} = \frac{10^8}{4 N_2 s n} \cdot v_{mean},$$

where s is the cross-section of the ring (in square centimetres), N_2 the

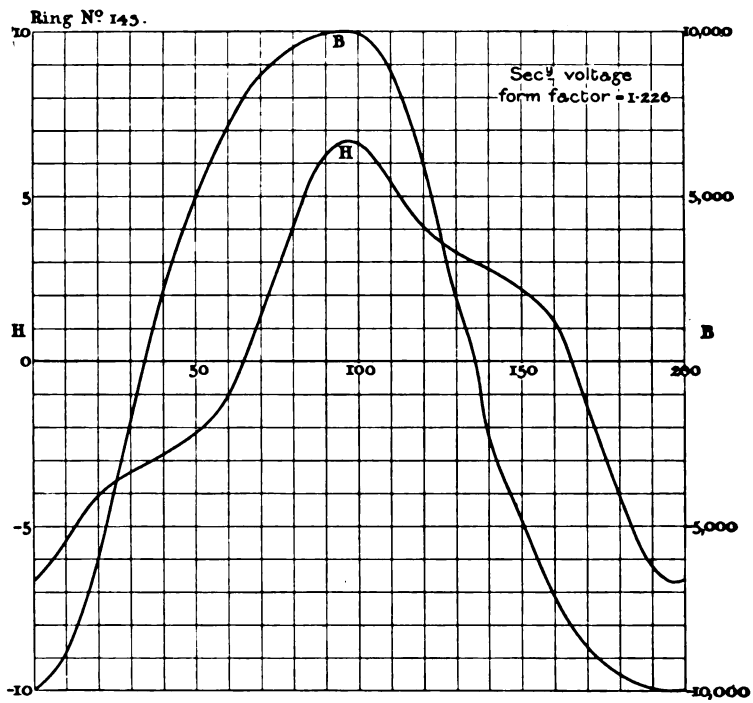

FIG. 2.

number of turns in Z, and n the frequency. If N_1 and N_2 are the numbers of turns in P r and S respectively, then the total power spent in the ring is equal to $(N_1/N_2) \times$ (watts read by wattmeter H). The wattmeter was a sensitive reflecting one, built mainly of white marble and ebonite to avoid eddy currents; with a moving current of 25 ohms and a total shunt resistance of 6,500 ohms, 1 watt (at 1 volt) gave 100 mm. at 1 m. This sensitivity allowed rings of small section to be tested without requiring an inconveniently large number of secondary turns. The transformer T had a core of Stalloy rings uniformly wound

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with primary turns (50 up to 400), and with 40,000 secondary turns. Thus various ratios up to 1 : 800 could be obtained. Its primary circuit took such a small current that putting it in circuit scarcely affected the galvanometer reading or that of the wattmeter. The frequency teller was of the type with a single vibrating strip which could quickly be adjusted to resonance with the actual frequency. It could be read to 1 in 500, and was carefully calibrated at each frequency used. Usually the temperature of the iron while under test was observed by the help of an iron-constantan thermo-junction inserted between the sheets before the ring was wound. With rings of large volume and high

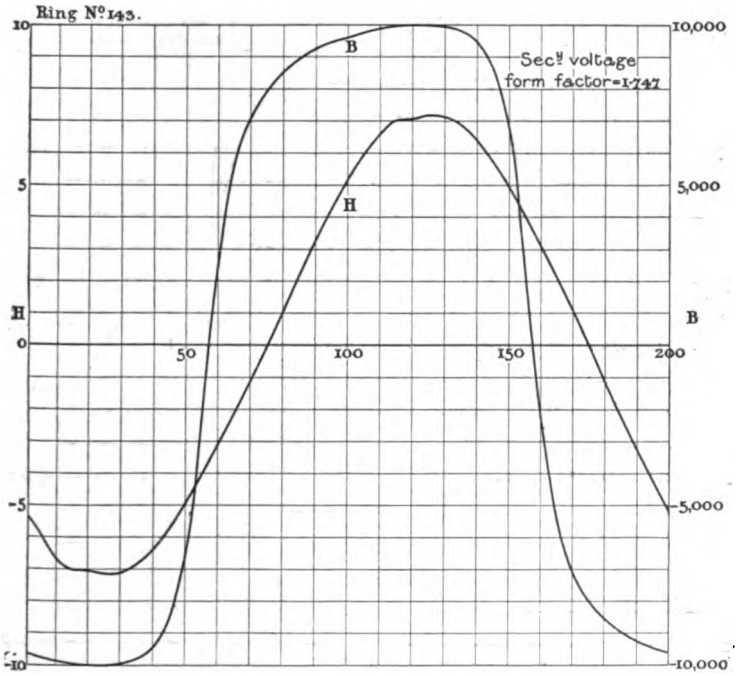

FIG. 3.

eddy current loss it is very necessary to know the temperature, especially when (as in nearly pure iron) the resistivity alters considerably with change of temperature. The results given below were corrected to standard temperature on the assumption that for such thin sheets (at the moderate frequencies used) the eddy current loss is inversely proportional to the resistivity.

§ 4. TYPICAL RESULTS.

In making the tests of total loss, in most cases it happened to be most convenient to keep the frequency nearly constant and to alter the

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form factor (f). This was done in several ways, *e.g.*, by altering the ratio of transformation of M and the resistances Q and R, by omitting M and connecting directly to A through a resistance, or by altering the number of primary turns used on the ring. Although the converter used gave almost exactly a sine-wave voltage, by these means it was found easy to obtain a wide range of form factor.* This is illustrated in Figs. 2, 3, and 4, which show three widely different cases with the same ring and the same machine, the curves for the magnetising current

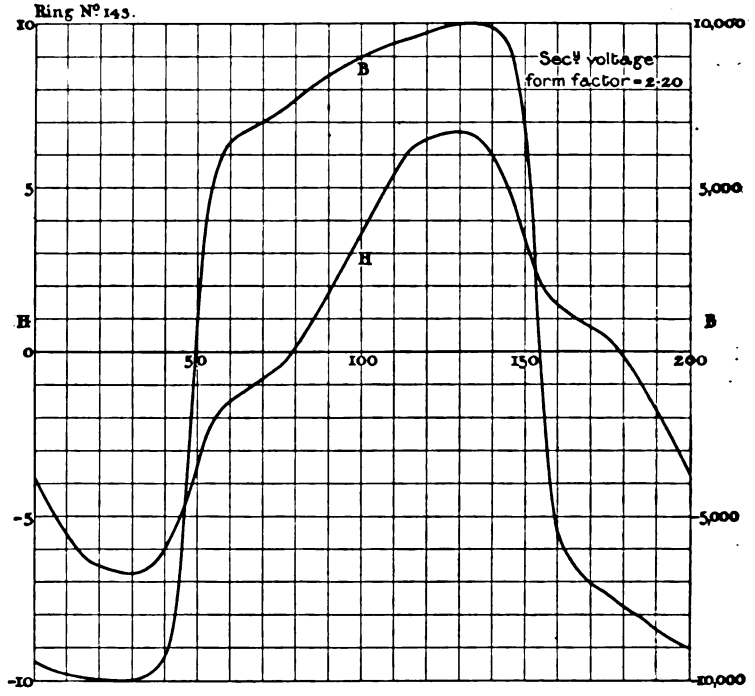

FIG. 4.

i_1 (and hence H) and the flux density B being drawn by Sahulka's and Townsend's methods with the commutator already mentioned. For i_1, the current i_1 is passed through the primary of an air-core transformer of known mutual inductance, whose secondary is connected to the commutator; for B the connections are as in Fig. 1. In both cases one pair of commutator brushes is shifted round to various angles and

* The lowest form factors of the secondary voltage were obtained with the greatest number of primary turns and the smallest transformation ratio and resistance, while the highest were got with few primary turns, no transformer, but considerable resistance in circuit.

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corresponding readings are taken on the galvanometer G. Complete curves of both i_1 and B can be drawn in about three minutes if the galvanometer is properly dead-beat.

From the observations already mentioned were deduced the total watts per kilogram, namely 50 w/n for 50 $\sim$ per second and $B_{max.} = 10{,}000$; and the values found were plotted against nf^2. Fig. 5 shows the curves thus obtained for a number of widely different materials, while Table I. gives for each of them the approximate thickness of the sheets, the resistivity, the permeability at B = 10,000, and the hysteresis coefficient η. The dimensions were found in the usual

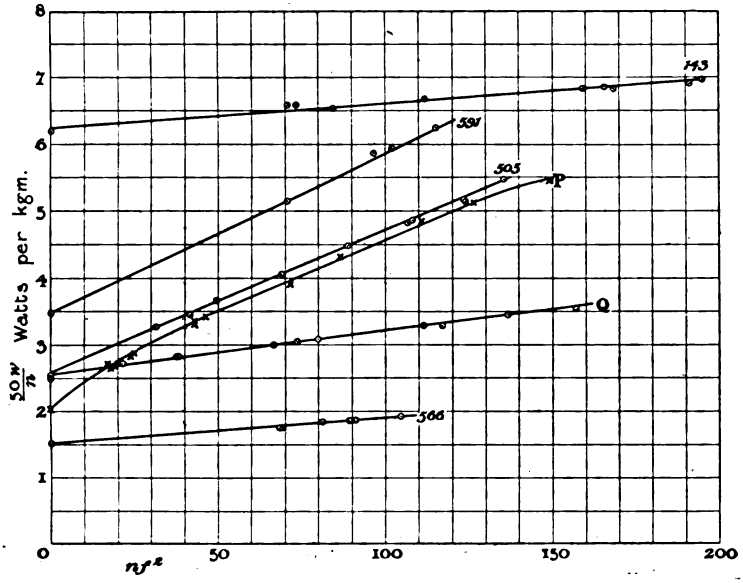

FIG. 5.

way by measuring the outer and inner diameters and determining the density and the total mass.

It may be mentioned that No. 591 was ordinary tinplate, (P) had been annealed at 800° C. and aged at 100° C., while (Q) and No. 566 were high resistivity materials.

To obtain the total loss at 50 $\sim$ per second for the standard conditions, namely, with induced voltage of sine-wave form (for which $f = 1{\cdot}111$), it is only necessary to read the ordinate of each curve for $nf^2 = 50 \times (1{\cdot}111)^2$, *i.e.*, 61·7. As the curves are practically straight lines near this value, if we wish to determine total loss alone, it is only necessary to take readings for two different form factors (or frequencies) not very far apart, join the points obtained (by a straight line), and find where the ordinate at $nf^2 = 61{\cdot}7$ cuts the joining line. This method of

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different form factors is very useful when the frequency cannot be varied—for example, in working with a public supply circuit or when the alternator is inaccessible. There is no need whatever to use a sine-curve machine, provided there are no dimples in either the H or B curves.

In Fig. 5, however, much more has been included. (*a*) The points shown for $nf^2 = 0$ are the values of the hysteresis loss obtained for each ring by the ordinary ballistic method; they are sometimes called the values of the "static hysteresis." (*b*) The points below $nf^2 = 50$ were obtained by using lower frequencies. (*c*) A few of the higher points were obtained with frequencies as high as 70 ∿ per second, the majority of the points, however, being for $n = 50$ ∿ per second.

TABLE I.

Sample.	Approximate Thickness of Sheets.	Resistivity at 15° C.	Permeability at B = 10,000.	Static η.
	Millimetre.	Microhm-cm.		
143	0·24	17·3	1,370	0·00384
591	0·46	12·6	1,868	0·00215
505	0·50	13·6	2,512	0·00158
P	0·43	14·0	2,878	0·00123
Q	0·40	43·0	1,873	0·00155
566	0·48	60·3	2,820	0·00090

Consideration of the curves in Fig. 5 leads to the following conclusions:—

1. For all the specimens except (P) the lines are practically straight and pass through the "static hysteresis" points. Hence, over the range of nf^2 shown, the hysteresis loss is constant, and the total loss per ∿ can be represented by the expression $F + G nf^2$, the two terms representing the hysteresis and eddy current losses respectively.

2. The specimen (P), on the contrary, shows a curve which is by no means a straight line, but clearly bends in coming down to the static hysteresis point. It also falls slightly at the higher values of nf^2. Except for the intermediate part of its range, the total loss cannot here be represented by the expression $F + G nf^2$. It is interesting to notice that (P) and (505) are very similar in total loss and also hysteresis, except at the upper and lower ends of the range.

The final conclusion is that, although some materials give excellent straight lines in the diagram of total loss for a wide range of frequency or form factor, other materials give lines that are distinctly curved,

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indicating that the hysteresis loss increases considerably as the frequency is raised from o upwards. There seems no doubt that this effect must be attributed to magnetic viscosity (see Lloyd, *loc. cit.*). In corroboration of this I may mention that, in the ballistic test of (P), if an additional evenly wound secondary circuit was kept closed during the test, a quite distinct alteration was shown in the values obtained for the permeability and hysteresis for $B_{max.} = 10{,}000$. The slight drop in the (P) curve at the higher values is probably due to "skin effect," the higher frequencies causing B to be not quite uniform throughout the thickness of the sheet. I should mention that several other samples gave lines bent similarly to that of (P).

The above results appear to throw some light on an old standing controversy. Several observers have stated that hysteresis loss is practically independent of frequency (at the lower values), while others affirm that it varies with frequency and wave-form. Gumlich and Rose incline to the former view, and Lloyd appears to agree with them. It seems likely, however, that some of the experimenters have been testing specimens like (505) and (591), while others have had experience of more abnormal materials like (P).

§ 5. Effect of Thickness of Sheets.

The experimental results for total loss at $B_{max.} = 10{,}000$ are only strictly valid when the thickness of the sheet is such that $B_{max.}$ has time to get practically uniform throughout the thickness in each half-period. To investigate this point experimentally a set of specimens of different thicknesses, but of as nearly as possible similar material, were tested for total loss. The material was "electrical steel," made by Messrs. J. Lysaght, Ltd., who have kindly permitted the results to be published.

Fig. 6, curve (*a*) shows the results obtained for eddy current loss with (mean) $B_{max.} = 10{,}000$, and $n = 50 \sim$ per second. In the same Fig. curve (*b*) is the theoretical curve calculated, on the assumption that the permeability is constant, by the formula of J. J. Thomson, as given by Russell.* The formula states that the eddy-current loss, for given *constant* permeability μ, resistivity ρ, and frequency n, varies as—

$$\frac{\sinh 2ma - \sin 2ma}{\cosh 2ma + \cos 2ma},$$

where—

$2a =$ thickness of sheet

and—

$$m = 2\pi \sqrt{\mu n/\rho},$$

ρ being in absolute units.

It will be seen that the two curves agree as well as could be expected, considering the uncertainty due to want of uniformity of material. For the smaller thicknesses the eddy-current loss is pro-

* A Russell, "Alternating Currents," vol. i., pp. 360 and 362.

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portional to the square of the thickness of the sheet. The agreement of the two curves in Fig. 6 only has reference to the variation in thickness, for they were arranged to coincide at one point. The absolute results given by the complete formula are less than those observed by large amounts varying from 10 to 100 per cent. according to the material, showing that the want of constancy of the permeability and the co-existence of hysteresis largely modify the conditions.

§ 6. Proper Dimensions of Ring Stampings.

In almost all magnetic tests there arise difficulties due to the alteration of the material due to the mechanical processes used in preparing

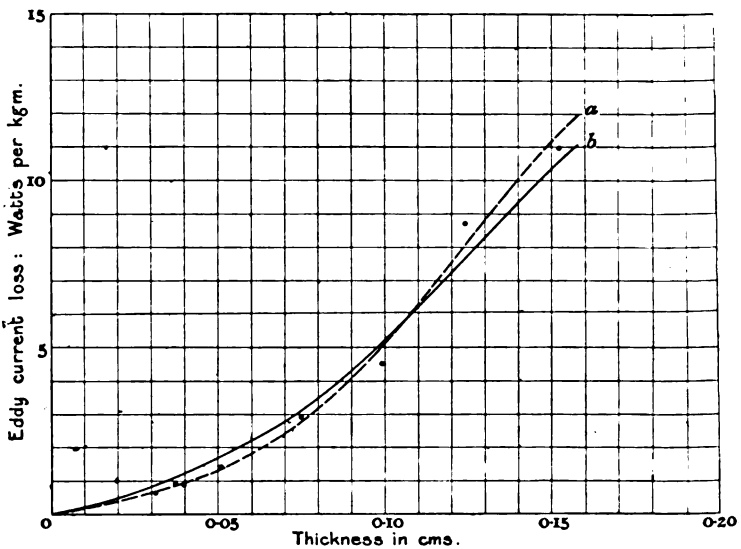

Fig. 6.

the test-pieces, such as stamping, cutting, or turning. The greater the width of the test-piece (whether ring or strip), the less the result will be affected by the edge hardening. In the case of rings, however, the radial width must not be taken too large in relation to the mean diameter, otherwise the magnetic force will not be sufficiently uniform over the width, being greater at the inner edge than at the outer. The same remark applies to almost any arrangement of strips, such as those used in building up the square of the Epstein apparatus. Thus, if it is not allowable to obliterate the effects of the mechanical treatment by annealing after stamping or cutting, the proportions of the test-pieces must be fixed by making a compromise between the two conditions—namely, maximum width of strip and greatest uniformity of H.

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The question of the amount of error in the usual energy determinations, due to the want of uniformity of H, has been very fully worked out by Richter * for rings of rectangular section, and lately his results for the simple case, where the permeability is constant, have been clearly tabulated by Lloyd,† who has also investigated the case of a ring of circular section. Lloyd points out that his results would be somewhat modified in practice because of the permeability not being constant. He mentions that the errors in the energy loss depend on the difference between (mean $B_{max.}$)$^{1\cdot6}$ and the mean of ($B_{max.}$)$^{1\cdot6}$ over the width of the ring. When working with $B_{max.} =$ 10,000, I found that the assumption of constant permeability may exaggerate the errors considerably. As this value of B has been much used in standard tests, I think it will be of interest to describe briefly my calculations.

Let the ring (of rectangular section) be divided into a number of elementary annuli of equal radial width. If the mean radius of one of these be r, then for that annulus $H = 2 N_1 I_1/10 \pi r$ or $H \propto 1/r$. If now the curve H B be known, we can find the value of B for each annulus, choosing the medial value near 10,000 for example. In a test of total loss it is the (mean $B_{max.}$) that is observed, the mean being taken over the width of the ring, and the hysteresis loss corresponding to this value should be proportional to (mean $B_{max.}$)$^{1\cdot6}$, but the loss actually measured by the wattmeter is proportional to the mean of ($B_{max.}$)$^{1\cdot6}$. The ratio of the first of these expressions to the second is accordingly the correcting factor to be applied to the observed hysteresis loss.‡

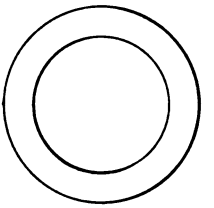

FIG. 7.

As examples, I have in this way worked out the correcting factor for two actual rings, one of very low, and the other of high hysteresis constant ($\eta = 0\cdot00083$ and $\eta = 0\cdot0042$ respectively). Each ring (Fig. 7) had an inner radius of 6 cm. and an outer of 8·5 cm. For $B_{max.} =$ 10,000 the correcting factors come to 1·0008 and 1·002 respectively, showing that, for a mean diameter of 14·5 cm., in each case the error in hysteresis is negligible with a radial width of 2·5 cm. If the permeability had been assumed constant the correcting factor would have been about 1·011 in both cases. It must be remembered, however, that for lower values of $B_{max.}$ (*e.g.*, 5,000) the variation in permeability would often make the correcting factor *greater* than for constant permeability.

We have investigated in various ways the effect of stamping, but it will be enough to describe one experiment. From a batch of carefully annealed sheets two sets (1) and (2) of ring stampings were made, having radial widths of 1·5 and 2·5 cm. respectively. On testing each

* *Elektrotechnische Zeitschrift*, vol. 24, p. 710, 1903.

† *Bulletin Bureau of Standards*, vol. 5, p. 435, 1909.

‡ The index 1·6, though not necessarily the true value for some specimens, is near enough to indicate the magnitude of the correction. The method was pointed out to me several years ago by Mr. G. F. C. Searle.

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set the ratio of their hysteresis losses was found to be 1·076. If we assume that the same width of edge is hardened in (1) and (2), then it is easy to show that the ratio of the loss for 2·5 cm. width to that for infinite width is 1·126. Thus we see that even with a width of 2·5 cm. the stamping has increased the mean hysteresis loss by over 12 per cent. Some experiments show less and some more than the above (according to material), but it is clear that for widths of the order of 3 cm. the effect of stamping is considerable, and some allowance would have to be made for it if absolute, and not merely comparative results are to be considered. The effect on the total loss will not be so great, as the eddy current part is not so much influenced.

In conclusion, I have to express my best thanks to Messrs. J. Lysaght, Ltd., for kind permission to publish results obtained on samples of their materials (*e.g.*, those in § 5); my thanks are also due to Messrs. H. C. H. Booth and T. L. Eckersley, whose skilful assistance was invaluable both in the experiments and in the reduction of results; and, finally, to Dr. R. T. Glazebrook, for his valued help and advice.

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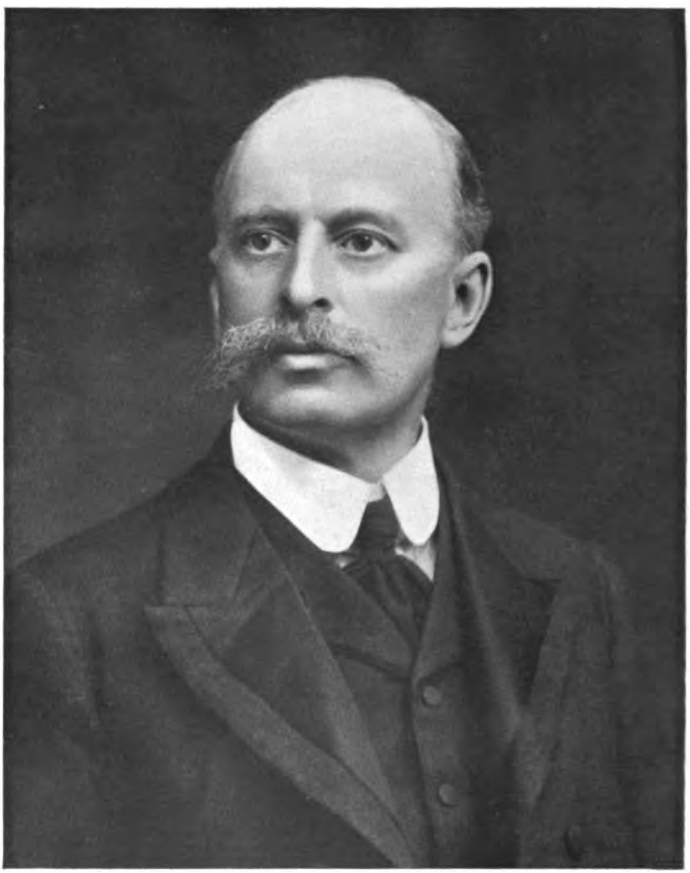

W. M. Mordey.

PRESIDENT 1908-9

The Institution of Electrical Engineers.

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JOURNAL

OF THE

Institution of Electrical Engineers.

Founded 1871. *Incorporated* 1883.

VOL. 43. 1909. No. 198.

Proceedings of the Four Hundred and Ninety-fifth Ordinary General Meeting of the Institution of Electrical Engineers, held in the Rooms of the Royal Society of Arts, John Street, Adelphi, W.C., on Thursday evening, May 13, 1909—Mr. W. M. MORDEY, President, in the chair.

The minutes of the Ordinary General Meeting, held on May 6, 1909, were taken as read, and confirmed.

The list of candidates for election into the Institution was taken as read, and it was ordered that it should be suspended in the Library.

The following list of transfers was announced as having been approved by the Council:—

TRANSFERS.

From the class of Associate Members to that of Members:—

Rooke Ainsworth.	Charles Frederick McInnes.
Joseph H. Dobson.	Hal Williams.

From the class of Associates to that of Members:—

Frederick P. Aulton,

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From the class of Students to that of Associate Members :—

Alfonso Castello-Sosa.	Harry Reginald Mills.
Richard P. M. Cauty.	William Hugh C. Prideaux.
Stewart N. Clarkson.	Charles Ernest Sexton.
Charles Wilson Crosbie.	Ernest William Short.
Alex. Lindsay Glegg.	Alfred E. Turpin.
Maurice Gregory.	Frederick Ralph Unwin.

Arthur Reginald Wood.

Messrs. H. G. Solomon and Alan Williams were appointed scrutineers of the ballot for the election of new members, and, at the end of the meeting, the following were declared to have been duly elected :—

ELECTIONS.

As Members.

George Leonard Andrews. | John Charles Taylor.

As Associate Members.

Charles Louis Almers.	Arthur Dimmack.
William Roxburgh Brash.	Harry Joseph Fisher.
Henry Burkinshaw.	Colin Stuart Hann.
John Henry Butters.	Henry Hawkins.
Walter Evans Chappell.	Samuel James.
James Frazer Clunas.	Knud Christian Knudsen.
John Collinge.	Samuel Mathews.
John Francis Crowley, B.A.	Thomas Reginald James Orr.
Joseph James Denton.	Horace James Quilter.

John Wilson Speight.

As Associates.

Lieut. Manuel Moreno. | John David Morgan.

Robert Vinçotte.

As Students.

Douglas V. Crowe.	Ronald William Manifold.
Frank George Griffith.	Frederick Howard Souden.

Donations to the *Library* were announced as having been received since the last meeting from Charles Bright, F.R.S.E., J. H. Dobson, W. Duddell, F.R.S., the Physikalisch-Technische Reichsanstalt, and the Smithsonian Institution, to whom the thanks of the meeting were duly accorded.

A paper (see page 567) by Mr. A. J. J. Pfeiffer, entitled "Economics of Medium-sized Power Stations : a Study of Comparisons between Steam, Gas, and Oil Engines," was read and discussed.

The meeting adjourned at 9.45 p.m.

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ECONOMICS OF MEDIUM-SIZED POWER STATIONS.

A STUDY OF COMPARISONS BETWEEN STEAM, GAS, AND OIL ENGINES.

By A. J. J. PFEIFFER, Member.

(*Paper received April 7, and read in London May* 13, 1909.)

INTRODUCTION.

Much has been written and discussed on the comparative merits and demerits of gas *versus* steam prime movers in central station practice, but comparatively little seems to be generally known of the rapid development of a third factor which is making itself felt in this field, and this is the internal combustion oil engine working on the Diesel principle. Although in successful operation for many years and covering a total of several hundreds of thousands B.H.P. in actual use, this type of engine up to quite recently was so limited in maximum output per unit that it remained almost a negligible factor in power station development.

Like the gas engine, however, the oil engine has received considerable attention during the past few years, until to-day the largest single unit running has an output of 800 H.P., and manufacturers are prepared to construct units up to 4,000 B.H.P.

The oil engine has, therefore, even at present a very considerable scope, and it is quite probable that the study of this type of economical prime mover will interest engineers connected with very large supply or power companies, who may find it profitable to consider it for their central stations as well as an alternative to sub-station plant, especially where transmission distances would necessitate large capital expenditure.

The object of this paper is to give a short description of the principles involved in the modern internal combustion oil engine, its method of working, its advantages and limitations from the standpoint of economy of operation as compared with gas and steam engines.

The following references to "oil engines" cover only those working on the Diesel principle, since only that type up to the present is constructed in sizes large enough to be considered a factor in central station design.

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The Internal Combustion Oil Engine.

Principles of Operation.—As far back as 1862 Beau de Rochas, during his investigations to reduce the high consumption of gas per horse-power in the gas engine as developed up to that time, gave the first indication of the cycle of operation which formed the basis of the successful development of the gas engine as we now know it. He pointed out the importance of high pressures at the beginning of the working stroke, and also the possibility of igniting the charge by the heat of compression.

This automatic method of ignition was made use of by Diesel in his engines.

The cycle of such an engine follows the 'general principles laid down by Rochas and is as follows :—

1. Air at atmospheric pressure and temperature is drawn into the cylinder.
2. This air is compressed to about 450 to 500 lbs. per square inch and becomes heated far above the ignition-point of oil, the temperature being about 900° F. to 1,000° F.

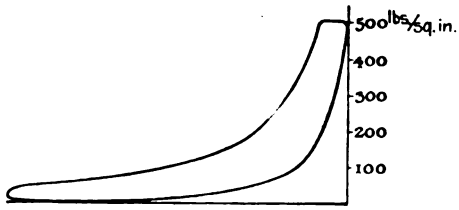

Fig. 1.—Indicator Diagram of a Diesel Oil Engine.

3. Oil fuel is blown into the cylinder 1° or 2° before the completion of the compression stroke (by means of air compressed by a special pump) at a constant pressure of 700 to 800 lbs. per square inch, depending upon the nature of the oil used.

   During the first part of the stroke the combustion, over a period determined by the amount of fuel to be sprayed in, is carried on at practically constant pressure, and thereafter the products of combustion do work by expansion (see indicator diagram, Fig. 1).
4. The waste gases are exhausted to atmosphere, the exhaust pressure at the cylinder being about 40 lbs.

The principal difference between the Diesel oil engine and the ordinary gas engine lies in the fact that only the air used for combustion is compressed, the fuel being gradually injected after this compression of the air has taken place, the resultant great advantage being the elimination of the possibility of premature ignition, no sudden increase of pressure and, therefore, less strain on the working parts.

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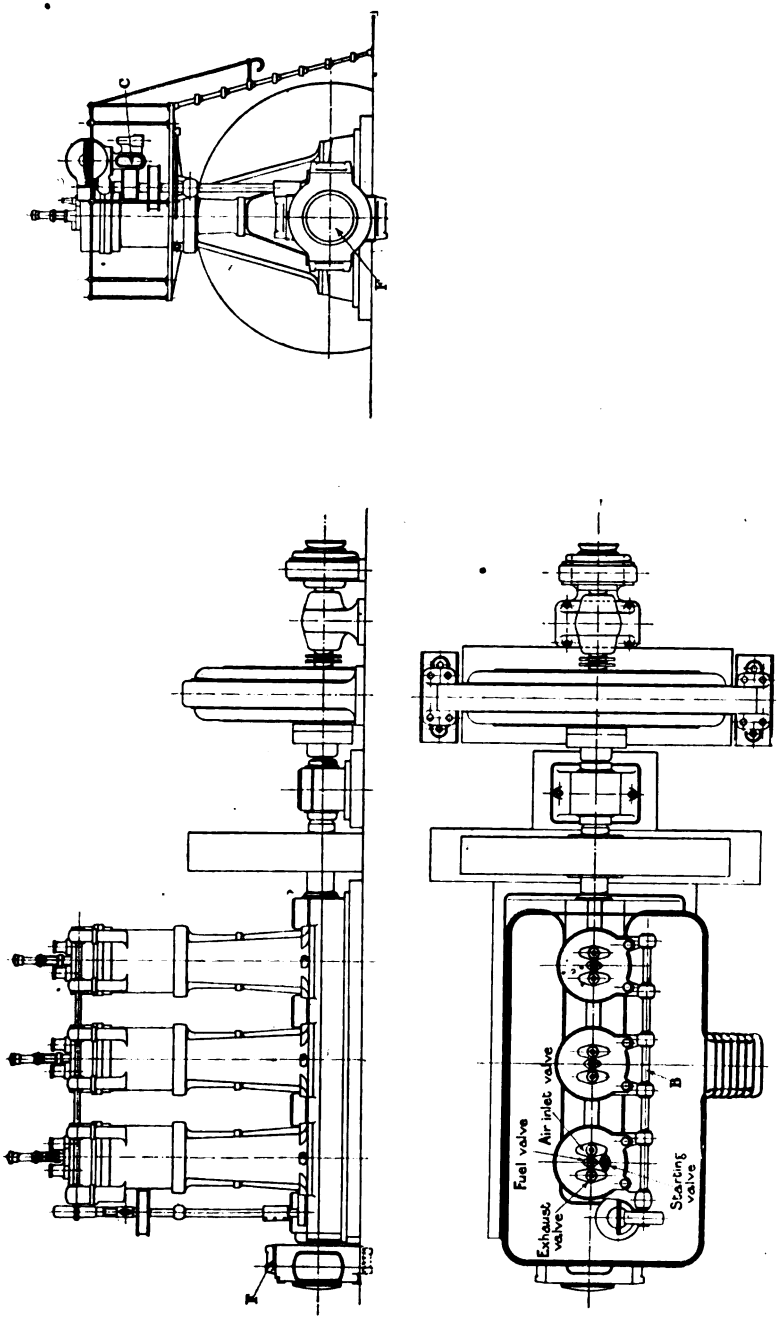

FIG. 2.—Outline of a 3-cylinder Single-acting 4-cycle Diesel Engine.

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Manufacturers of Diesel engines are now following closely in the footsteps of the gas-engine development, and are adopting the 2-cycle and also the double-acting principle for large units, giving one, two, or four working strokes per revolution. To obtain the 2-cycle result, the principle of scavenging is resorted to by blowing fresh air at a pressure of 5 lbs. into the cylinder near the end of stroke 3, clearing out the waste exhaust gases, and filling the cylinder with a new charge : Strokes 1, 3 and 4 of the 4-cycle engine are thus combined.

While the above are the general principles which govern the operation of the type of oil engine under discussion, the following will be of interest as an outline of a typical plant and its general method of working :—

Details of construction of parts will not be dealt with, as that does not come within the scope of this paper.

Fig. 2 shows an outline of a 3-cylinder single-acting 4-cycle engine of the vertical type, and Fig. 3 the general arrangement of a complete plant having five 400-k.w. units installed.

As can be seen in Fig. 2, each cylinder is provided with three valves, viz. :—

Exhaust,
Inlet for air,
Inlet for fuel,

one cylinder, in addition, being supplied with a starting valve. These are opened and closed by cams and springs respectively, the cams being attached to the common shaft B having half the speed of the engine shaft.

C represents the fuel pump, the plunger of which is driven directly from the vertical shaft S. By an arrangement of levers and eccentrics, connected to the governor, the time is regulated during which the suction valve is kept open, thus determining the amount of fuel for varying loads. In the earlier types of engines it was customary to provide each cylinder with its own fuel pump, but of late it has been found simpler to accomplish the feeding by one pump and fuel circuit for all cylinders, thus assuring an equal amount of fuel to each cylinder at all loads.

F represents the 3-stage air compressor direct coupled to the engine. This takes in fresh air, compresses it in three stages to 75, 400, and 750 lbs. respectively, the air being cooled after each stage by passing through water-cooled chambers.

The compressed air is stored in G (Fig. 3), and serves to inject the fuel into the cylinder against the high cylinder pressure.

The air-starting reservoir H is connected by an overflow valve with the air-blast reservoir, and is used for starting the engine.

K is a silencing chamber to reduce or eliminate the noise of exhaust.

The water-circulating pump, marked L, serves to force cooling water through the water jackets of the engine cylinder, air pump, and

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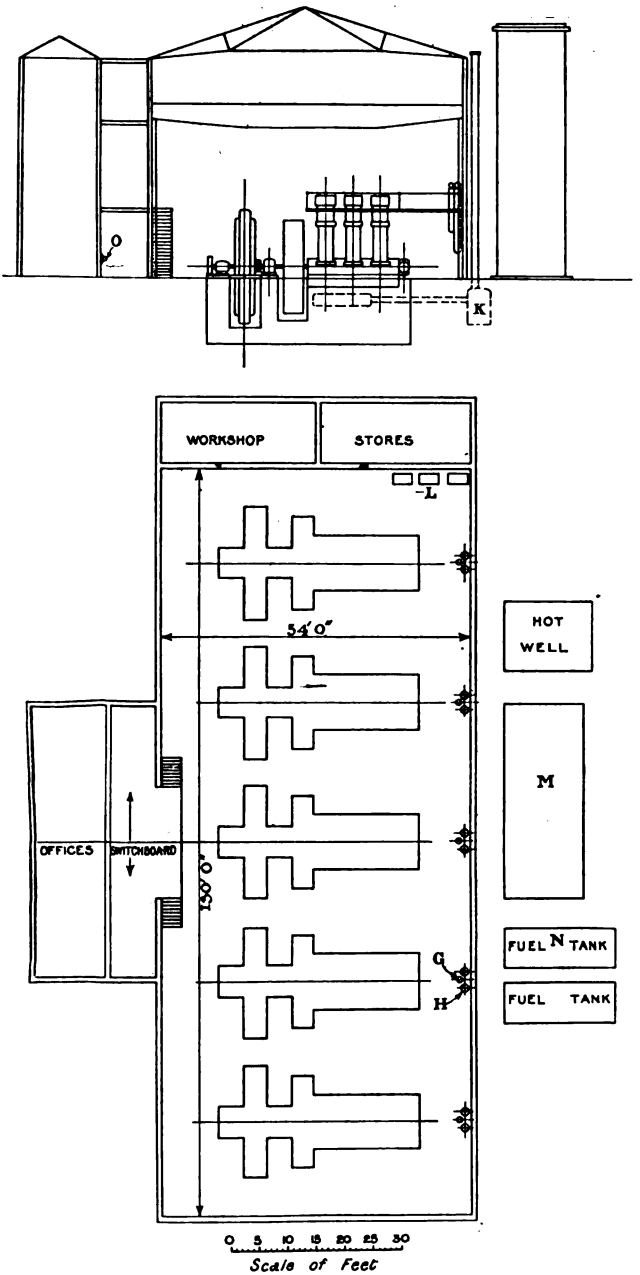

FIG. 3.—General Arrangement of Diesel Oil-engine Plant, 5 Units 400 k.w. each.

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cooling chambers, and from there up to the top of the cooling tower M.

N is the fuel storage reservoir.

O represents the fuel service pump for raising the oil from N to the overhead service reservoirs, from which the fuel is fed to the fuel pump by gravity.

The engine is started off as an air engine by compressed air stored in H during a previous run, the pressure being about 750 to 800 lbs. per square inch. When the engine has attained practically full speed the fuel valve is made to engage the cam and ignition takes place. The starting-valve lever is at the same time thrown out of gear and the engine is ready for work.

This operation is carried out by one man, and is completed in from 1 to 2 minutes.

Thermo-dynamic Efficiency.—An oil-engine plant burning crude petroleum of about 18,500 B.Th.U. per lb. has a thermo-dynamic efficiency far exceeding that of a steam or gas plant, this efficiency remaining practically constant over a wide range of sizes of units, and is about as follows:—

Overall Thermo-dynamic Efficiency at Full Load.

	Per Cent.
Calorific value of fuel	100
Loss in exhaust, cooling, and radiation	55
I.H.P.	45
Loss—engine friction and air pump	11
B.H.P.	34
Generator loss at 91 per cent. efficiency ...	3
Efficiency of complete set at full load	31

The auxiliary plant losses in addition to the air pump are very small and do not reach ½ per cent.

For varying loads, the following figures are a close approximation :—

Loads.		
½	¾	Full.
24·8 per cent.	29·2 per cent.	30·5 per cent.

Sizes of Units.—The sizes of oil engines working on the Diesel principle have, as above stated, increased rapidly of late. Three to four years ago a 450-B.H.P. unit was the largest actually running, while to-day there is in service a vertical 800-B.H.P. set of 4-cylinder single-acting 4-stroke type, having a speed of 150 revs. per minute. This latter engine has only the cylinder and air pump water jacketed, and it is probably the limit of size to which engines can be constructed without having recourse to water cooling the piston, exhaust valves, etc.

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For larger outputs some manufacturers are devoting themselves to the development of the 2-cycle engine, the largest at present running being of 750 B.H.P., while others of equal repute are adhering to the simpler and less complicated 4-cycle principle, their latest design being based on the horizontal twin-tandem double-acting type giving four working strokes per revolution, and on this design they are prepared to construct units up to 4,000 B.H.P.

Reliability and Simplicity.—As regards these two factors, so important in the operation of a central station plant, this type of oil engine leaves nothing to be desired, and as far as the latter factor is concerned the oil-engine plant is certainly much superior to either steam or gas.

The engine is started up a few minutes before work is expected of it, and, in consequence, the costly standby losses of a steam or gas plant, especially at low load factors, are entirely lacking. All labour in connection with fuel handling and boiler or producer plant is done away with, and, in consequence, the wages bill of an oil-engine plant is about one-half to two-thirds of that of steam or gas.

On the advice of the writer a 1,000-B.H.P. plant was installed for the Howrah system of the Calcutta Tramways Company, the largest unit being 450 B.H.P. This plant has been running for almost a year without a hitch of any kind, having passed through the period of guarantee without requiring the slightest repair.

Once the oil engine is thoroughly well installed and adjusted, there is much less to go wrong with such a plant than with either steam or gas, and the plant is, therefore, much more fool-proof, an important consideration in countries and places where skilled labour is scarce or very expensive.

Overload Capacity.—Like a gas engine the overload capacity of an oil engine is limited to about 15 to 20 per cent., and this must be taken into consideration in connection with plants designed on very close margins between maximum loads and total kilowatts installed.

Governing and Parallel Running.—The speed regulation approximates easily to that obtained in a steam engine, and can be made to come to within 3 per cent., or even less, between no load and full load.

As regards satisfactory conditions of parallel running, a speed variation of 1/250th to 1/300th can easily be obtained with a 4-cylinder 4-cycle single-acting engine with a small flywheel. To obtain the same result with three cylinders, however, requires a flywheel of cast steel, the use of the ordinary heavy cast-iron flywheel being advisable only for speed variations up to 1/160th. In connection with the high limits for speed variation usually insisted upon, it will be interesting to cite the case of parallel running of two 300-B.H.P. Diesel oil engines driving 50-cycle alternating-current generators in the works of the Daimler Motor Company, Coventry, where the flywheel was designed for a speed variation of 1/160th, the two sets working together without the slightest sign of trouble.

Noise and Smoke.—As central stations are, in a large number of

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cases, located in or near densely inhabited districts the noise of exhausts must, of course, be eliminated, and this is done by means of silencers mentioned on page 570. The noise can thus be effectively done away with so as to make it possible to operate a plant in the heart of a city without its becoming a nuisance. This is evidenced by a plant installed in the basement of a large business building in London.

Another point to be guarded against in working an oil plant in cities or towns where restrictions are severe is that of smoke, which comes into evidence when engines operate below $\frac{1}{3}$ to $\frac{1}{8}$ full load, the cause being the imperfect combustion of the oil fuel.

For plants having low load factors, therefore, it will be advisable, in addition to the advantage of economy, to put in at least one small unit to cope with light loads, or possibly to instal accumulators.

Fuel and Fuel Supply.—In considering the oil engine from an operative standpoint one of the first thoughts that strikes one perhaps is, "What is the reliability of fuel supply and the possibilities of price fluctuations?"

It may not be generally known, but it is a fact that the type of engine under consideration can burn almost any liquid fuel; but generally, and especially in Great Britain, petroleum residue from the Dutch East Indies, Texas, and Roumania is used, while on the Continent gas oils and paraffin oils are successfully employed.

Of late a new source of oil fuel has been found, and that is gas plants. Carburetted water gas plants, of which there are a great many in Great Britain, in connection with which gas oil is used to enrich the illuminating gas, give off an oil tar as by-product which lends itself admirably as oil-engine fuel, having a calorific value of about 0·9 that of crude petroleum or about 16,500 B.Th.U. per lb. Such fuel oil has already been used for some time past on the Continent in connection with Diesel oil engines.

Then, again, amongst the by-products of a retort gas plant using bituminous coal is a tar oil, this containing asphalt which has to be removed before the oil can be used.

As crude petroleum is found in a great many parts of the world, as indicated by black dots in Fig. 4, and as new fields are being continually discovered, the reliability of supply and price fluctuations may be regarded as no worse than coal.

Crude petroleum residue costs at present between 50s. and 55s. per ton at ports in England; in South America about 60s. per ton, and in Indian ports about 45s. to 50s. per ton.

Comparisons of Capital and Operating Costs for Steam and Gas *versus* Oil Plants.

As this paper is intended to cover only comparisons of medium-sized stations, it will be possible to base calculations upon actual experience with Diesel oil engines, leaving the possibility of utilising

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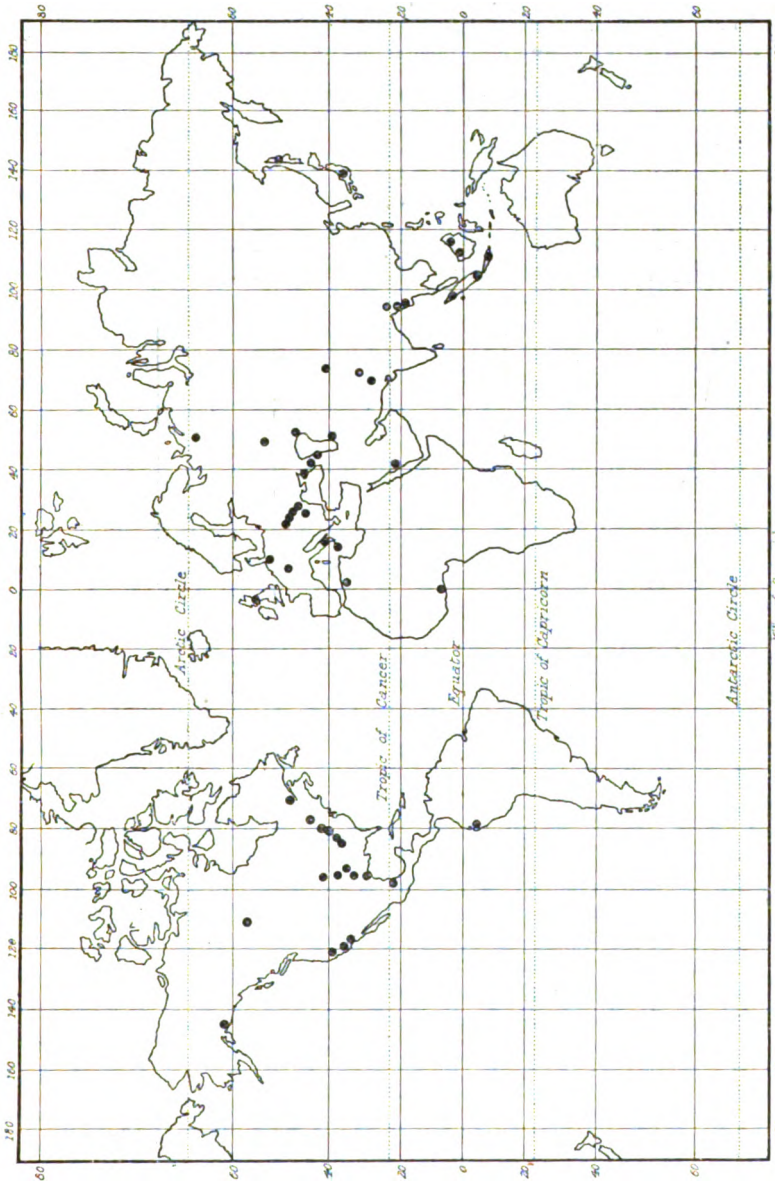

FIG. 4.—Location of the World's Oilfields.

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larger units and the study of their relative economies to be investigated by the engineer as occasion requires.

In a comparison of economy of operation between the three types of installations, the more important factors to be considered are :—

Fuel consumption.
Load factors.
Fuel costs.
Labour costs.
Capital costs.

After having worked out the comparative limitations of economy for each type, there still remains to give due consideration to the factors

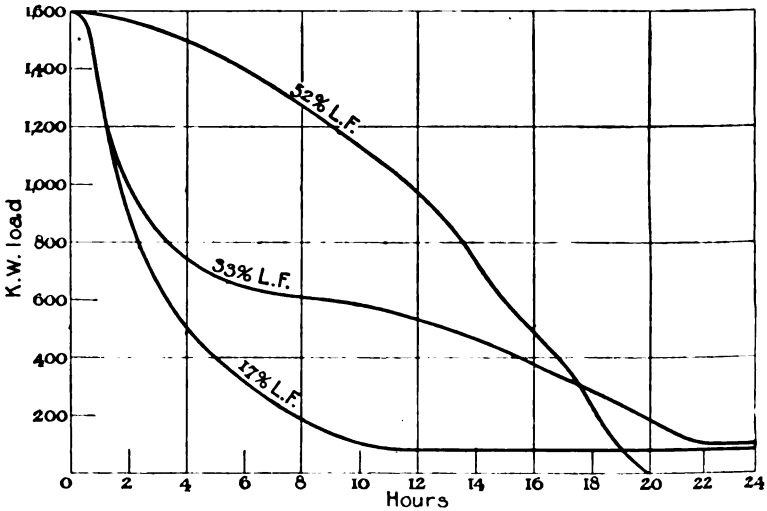

FIG. 5.—Plant Load Hours.

of reliability and simplicity ; but as these are considerations governed to a large extent by individual opinions, they are perhaps best left out of the following calculations.

Details of Plant chosen as Basis of Comparison.—Let us assume the case of a plant dealing with a maximum effective load of 1,600 k.w. and consider three types of loads having the following annual load factors :—

$$\left(\frac{\text{B.Th.U.} \times 100}{\text{maximum load} \times 8{,}760}\right).$$

Lighting Load.	Lighting and Power Load.	Traction Load.
17·5 per cent.	33 per cent.	52 per cent.

On Fig. 5 are shown graphically the plant load hour curves resulting from the ordinary daily load characteristics over the twenty-four hours

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of these three types of loads. These curves indicate the periods during which certain loads on the station are maintained, and for the sake of simplicity it is assumed that these characteristics are the same for every day in the year.

The divisions of engine units are assumed as follows :—

Load Factor.		
17·5 per Cent.	33 per Cent.	52 per Cent.
Five 400-k.w. sets (1 reserve) One 100-k.w. set	Four 400-k.w. sets (1 reserve) Two 200-k.w. sets	Five 400-k.w. sets (1 reserve) —
2,100 k.w. installed	2,000 k.w. installed	2,000 k.w. installed

For all the above it is assumed that 5 (1 reserve) units are provided for both boiler and producer plants.

Capital Costs of Complete Plants.—In arriving at the capital expenditure involved for a complete plant, the following factors have to be given due consideration :—

Class of machinery.
Refinements of plant to obtain maximum economy.
Class of building.
Nature of foundations required.
Cost of sites.

With all these items appearing as variables, estimates of costs may be made to diverge considerably. The following figures of costs are based on high-grade plants throughout :—

(*a*) *Steam Plant.*

1. *Machinery, etc.*

High-speed vertical compound engines with direct-coupled generators.
Water-tube boilers, superheaters, and stokers.
Condensers, complete with pumps.
Economisers.
Cooling towers.
Auxiliary pumps, etc.
Piping.
Switchboard and c ıbling.
Crane.

Per kilowatt installed... ... ... £16·0

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2. *Buildings and Foundations.*
Steel-framed structure, brick lined.
Chimney.
Coal bunkers, coal handling.
Foundations for buildings and machinery. £8·5

Total per kilowatt ... ... £24·5

(*b*) *Gas Plant.*
1. *Machinery.*
Vertical engines (single-acting tandem) with direct-coupled generators.
Pressure-producer plant.
All necessary auxiliary machinery.
Cooling tower.
Piping.
Switchboard and cabling.
Crane.
Per kilowatt installed... ... ... £17·5

2. *Buildings and Foundations.*
Steel-framed structure, brick lined.
Coal bunkers, coal handling, etc.
Foundations. £6·0

Total per kilowatt ... ... £23·5

(*c*) *Oil Plant.*
1. *Machinery.*
Vertical 4-stroke engines, with direct-coupled generators, and all necessary pumps, air vessels, etc.
Piping.
Auxiliary pumps.
Cooling tower.
Switchboard and cabling.
Crane.
Per kilowatt installed... ... ... £19·5
For a 2-cycle engine the total cost per kilowatt... ... ... £17·5

2. *Buildings and Foundations.*
Steel-framed structure, brick lined.
Oil storage tanks, etc.
Foundations. £5·5

Total per kilowatt, from... ...£23 to £25

From the above it would seem that the difference of capital outlay between the three high-grade plants is but nominal. Land value has

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not been taken into account, as that is too erratic a variable and is usually comparatively small.

Fuel Consumption and Thermo-dynamic Efficiency.

(*a*) *Steam.*

To obtain a fair comparison with oil, a plant embodying most up-to-date characteristics to attain maximum economy has been assumed, *i.e.* :—

Engines—compound condensing.
Boilers—water tube, with superheaters and stokers.
Economisers, etc.
Boiler pressure—150 lbs. per square inch.
Superheat—100° F.
Vacuum—25°.
Steam consumption at full load, including auxiliaries—20·5 lbs. per kilowatt-hour.
Coal—13,000 units.
Water evaporated per lb. of coal—8 lbs.

(*b*) *Gas.*

Engine—vertical single-acting tandem.
Producer—pressure.
Coal—13,000 B.Th.U. per lb.

(*c*) *Oil.*

Engine—vertical single-acting 4-cycle.
Oil—18,500 B.Th.U. per lb.

The fuel consumptions on Table I. are worked out on the basis of—

1. Consumption per effective kilowatt-hour output,
2. Consumption covering standby losses,

and to these totals is added a certain percentage to cover inefficient handling, loss in efficiency in the plant, due to fouling of tubes and pipes, etc.

From the fuel consumption shown on Fig. 6 are derived the following :—

Load Factor.	Overall Thermo dynamic Efficiencies.		
	Steam Plant.	Gas Plant.	Oil Plant.
Per Cent.	Per Cent.	Per Cent.	Per Cent.
17·5	5·60	11·7	25·7
33·0	7·30	13·3	27·3
52·0	8·70	14·5	27·8

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These results show that even with a high grade and very efficient steam plant, the comparative thermo-dynamic efficiencies are approximately as follows :—

Oil engine ...	...	...	...	100 per cent.
Gas engine ...	...	...	...	46 to 52 per cent.
Steam engine	...	...	...	22 to 30 per cent.

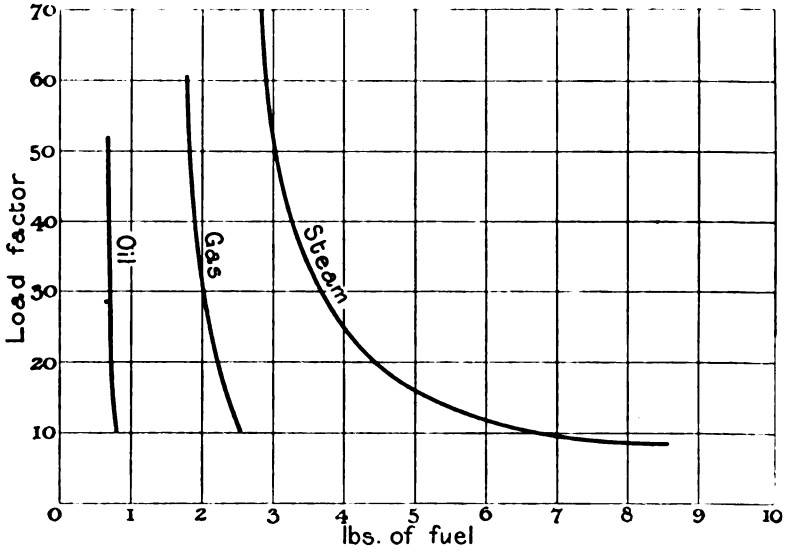

FIG. 6.—Total Fuel Consumption per Kilowatt-hour Generated.

The superiority of the oil-engine plant as regards thermo-dynamic efficiency is attributable to two principal reasons :—

1. Absence of standby losses.
2. Greater efficiency in the cycle of operation in the engine itself, the advantage gained over a gas engine in this latter respect being principally due to the much higher compression attained in the oil engine than is possible in a gas engine.

The above advantages are to a certain extent offset, however, by the greater driving losses of the oil engine, the mechanical efficiency of which, inclusive of the air pump, is only about 76 to 77 per cent.

The thermo-dynamic efficiencies for steam and gas plants given in the table on page 579 seems to agree very closely with results obtained from actual experiences in existing large stations.

If the overall thermo-dynamic efficiencies resulting from the assumed coal consumptions shown in Fig. 6 are plotted with respect to

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load factors, it will be found that the curves will pass very closely the points representing average results of 20 steam plants (reciprocating engines and turbines) varying from 2,000 to 22,000-k.w. output, and

TABLE I.

Fuel Consumption.

(Maximum Load, 1,600 k.w.)

Load Factor.	Steam Engine. Lbs. per Unit Generated.	Gas Engine. Lbs. per Unit Generated.	Oil Engine. Lbs. per Unit Generated.
17·5 per cent.	(1) ... 2·69 (2) ... 1·20 3·89 Add 20 % 0·78 Total lbs. 4·67	(1) ... ... 1·660 (2) ... ... 0·216 1·876 Add 20 % 0·375 Total lbs. 2·251	(1) ... ... 0·652 (2) ... ... 0 0·652 Add 10 % 0·065 Total lbs. 0·717
33 per cent.	(1) ... 2·650 (2) ... 0·440 3·090 Add 15 % 0·460 Total lbs. 3·550	(1) ... ... 1·630 (2) ... ... 0·089 1·719 Add 15 % 0·260 Total lbs. 1·979	(1) ... ... 0·630 (2) ... ... 0 0·630 Add 7½ % 0·047 Total lbs. 0·677
52 per cent.	(1) ... 2·60 (2) ... 0·20 2·80 Add 10 % 0·28 Total lbs. 3·08	(1) ... ... 1·620 (2) ... ... 0·040 1·660 Add 10 % 0·160 Total lbs. 1·820	(1) ... ... 0·63 (2) ... ... 0 0·63 Add 5 % 0·03 Total lbs. 0·66

NOTE.—(1) = Lbs. of fuel per B.Th.U. generated, representing effective work done.

(2) = Lbs. of fuel per B.Th.U. generated, representing standby losses.

Boilers at 13 lbs. per 1,000 lbs. steam.
Producer at 20 lbs. per producer hour.

8 gas plants from 200 to 2,000-k.w. output, as set out in the appendix to the paper, "The Use of Large Gas Engines for Generating Electric Power," * read before this Institution by Messrs. Andrews and Porter on February 11, 1909.

* *Journal of the Institution of Electrical Engineers*, vol. 43, p. 3, 1909.

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It will probably be possible to raise the efficiency of gas plants somewhat if the heat of the engine exhaust is made use of to aid in generating the steam required in connection with the producer plants.

TABLE II.

Total Works Cost per Effective Unit Generated.

(Maximum Load, 1,600 k.w.)

Load Factor.		Steam. Pence per Unit Generated.	Gas. Pence per Unit Generated.	Oil. Pence per Unit Generated.
17·5 per cent.	Fuel	At 15s. per Ton. 0·376	At 25s. per Ton. 0·300	At 60s. per Ton. 0·230
	Oil, waste, water, and stores	0·04	0·045	0·042
	Salaries and wages...	0·16	0·150	0·100
	Maintenance and repairs	0·09	0·090	0·064
		— 0·290	— 0·285	— 0·206
	Total	0·666	0·585	0·436
33 per cent.	Fuel	0·286	0·265	0·218
	Oil, waste, water, and stores	0·035	0·040	0·036
	Salaries and wages...	0·110	0·110	0·070
	Maintenance and repairs	0·070	0·070	0·050
		— 0·215	— 0·220	— 0·156
	Total	0·501	0·485	0·374
52 per cent.	Fuel	0·247	0·243	0·212
	Oil, waste, water, and stores	0·030	0·035	0·030
	Salaries and wages...	0·085	0·080	0·054
	Maintenance and repairs	0·060	0·060	0·042
		— 0·175	— 0·175	— 0·126
	Total	0·422	0·418	0·338

Total Works Cost.—On Table II. are tabulated details of the comparative works cost under the well-recognised headings, and for the various load factors assumed above.

(*a*) *Fuel.*—Fuel costs were taken at arbitrary figures with the idea of obtaining two points on the works cost curve, Figs. 7 and 8.

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(*b*) *Oil, Waste, and Stores.*—These figures approximate fairly closely to results obtained in operating plants of about the same size.

(*c*) *Wages and Salaries.*—This covers workmen, etc., and does not include management. It will be noted that oil-engine plant charges for this item are about two-thirds that of steam,

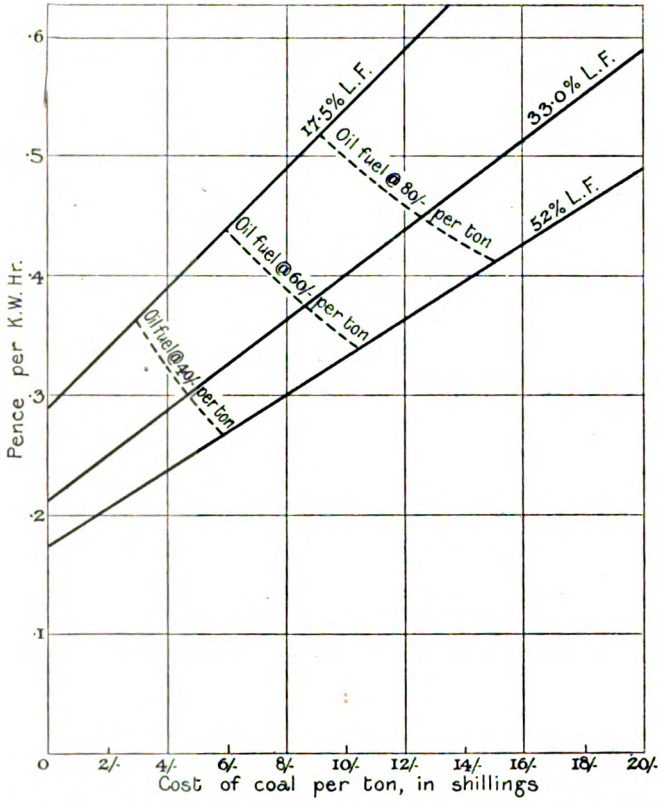

FIG. 7.—Steam Plant. Works Cost—Pence per Kilowatt-hour Generated.

for reasons explained in paragraph on reliability and simplicity.

(*d*) *Maintenance and Repairs.*—This is always a debatable figure, subject to great variations in different stations, and depends, of course, primarily upon the quality of the plant installed, how hard it is worked, the care taken, or the amount of abuse it is subjected to. Certainly the oil-engine plant having no boiler or producer plant to go wrong will be

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lower as regards this item, and the figure assumed can probably be considered as fair.

(*e*) *Interest and Depreciation.*—Depreciation is a factor involving so many variables that it is difficult to give a satisfactory rate to cover general conditions, and if obsolescence and inadequacy are likewise to be given consideration, the divergence of individual opinion becomes still greater.

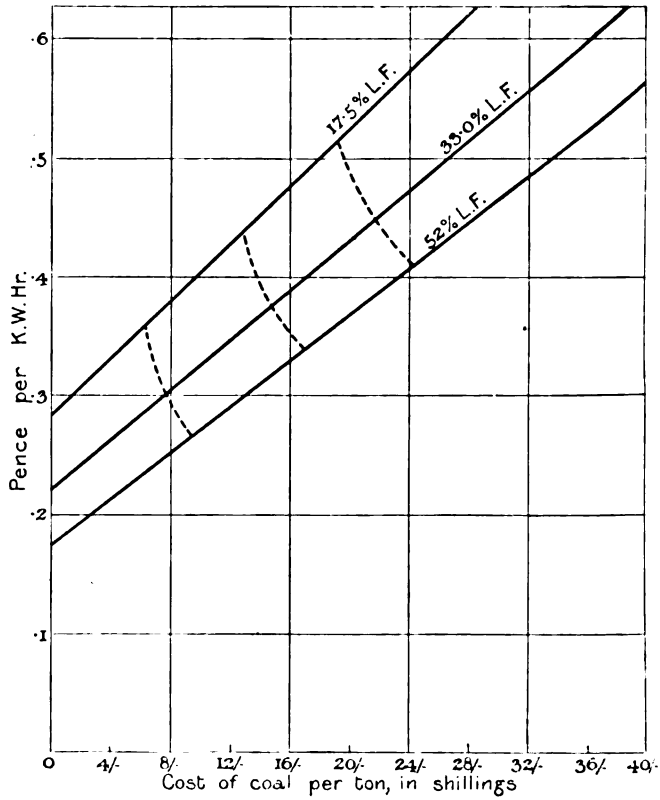

FIG. 8.—Gas Plant—Pence per Kilowatt-hour Generated.

As regards Diesel engines, experience with running plants covers about eleven years, and based on these results, coupled with the fact that the engines made to-day embody no radical changes in construction or operation, it is quite safe to assume that the life of a Diesel engine is equal to that of a steam or gas plant.

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Conclusions : (*a*) *Parity Curves.*—In Figs. 7 and 8 are plotted graphically the results shown on Table II., for total works cost per effective unit of output for steam and gas plants respectively, at different load factors and varying prices of coal.

The dotted lines are what may be termed "parity curves," the inter-

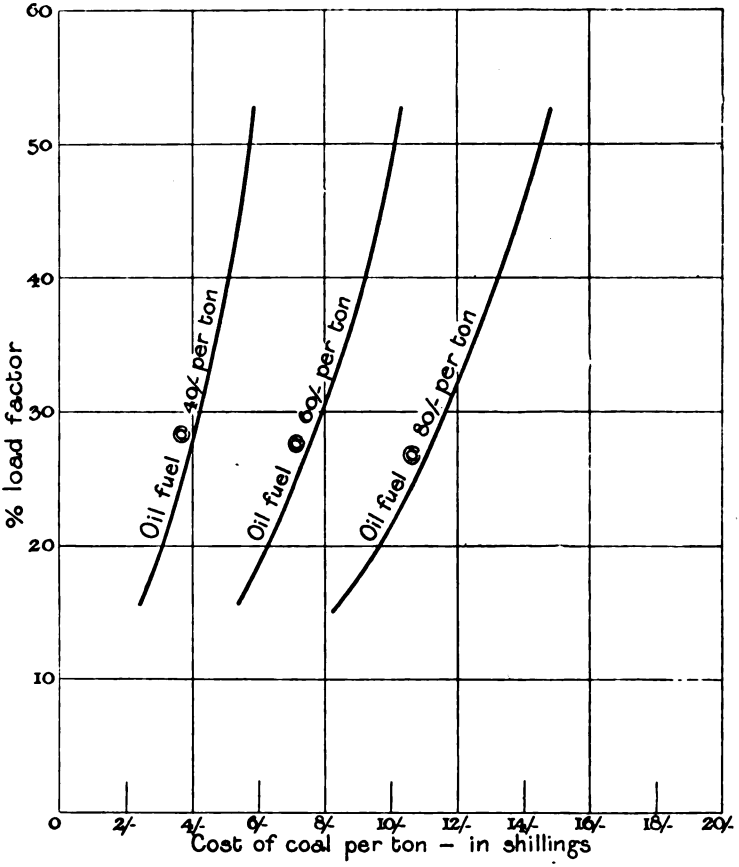

FIG. 9.—Steam *versus* Oil—Parity Curves.

sections with the works cost curves indicating the price of coal at which the total works cost of steam and oil or gas and oil plants are equal, under various assumptions of oil costs.

To arrive at a simpler basis of comparison, these intersecting points may be plotted in terms of coal cost and load factors, resulting in curves as shown on Figs. 9 and 10.

With a given load factor and given cost of oil fuel, one can at once

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find the limiting price for coal, beyond which the oil-engine plant would be more economical, as for example :—

With load factor... ... ... 20 per cent.
Oil fuel ... ... 60s. per ton.
The limit of cost of coal per ton { 6s. 4d. for steam. / 13s. for gas.

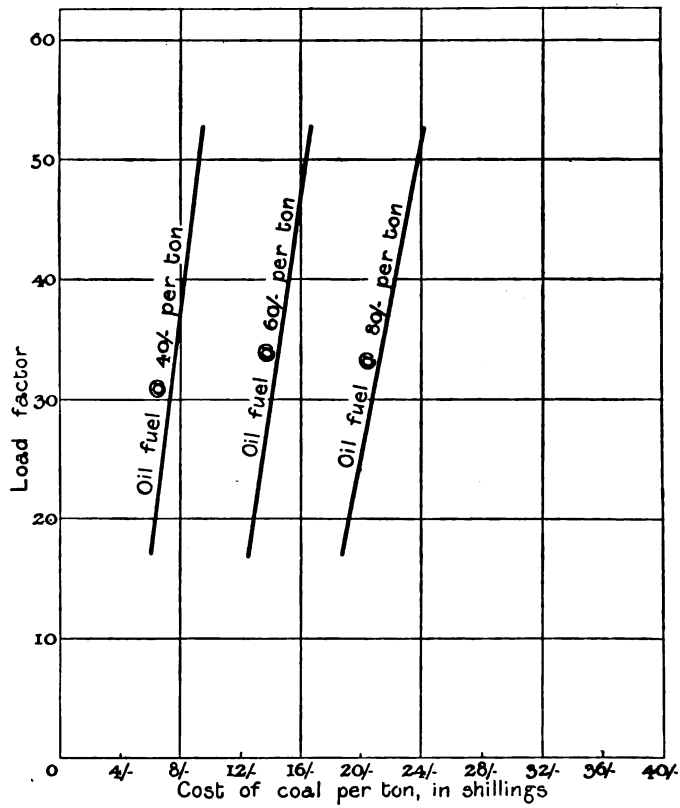

FIG. 10.—Gas *versus* Oil—Parity Curves.

(*b*) *Savings Effected.*—If we go a step further than the "parity curves" shown on Figs. 9 and 10 and plot the savings per kilowatt-hour effected by the oil-engine plant under certain assumptions of constant oil fuel costs and varying coal costs, we arrive at results given in the curves of Figs. 11 and 12, where cost of crude petroleum has been taken at 60s. per ton, which is a close approximation to the average selling price in Great Britain.

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These curves cover savings in works cost only. There still remains to consider the effect on these curves of the following fixed charges :—

1. Interest and depreciation.
2. Management, office expenditure, etc.
3. Rents, rates, and taxes.

As the capital costs of high-class steam and gas plants of medium

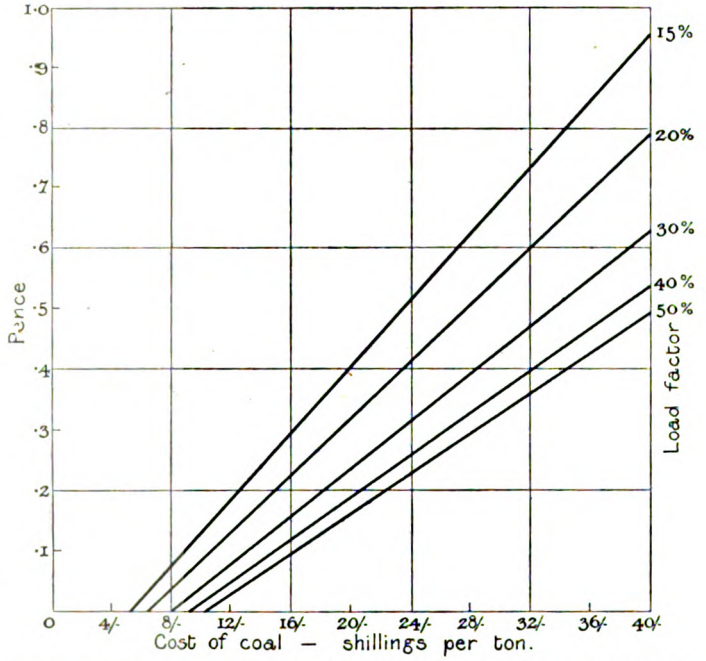

FIG. 11.—Steam *versus* Oil—Savings Effected by the Oil-engine Plant in Works Cost per Kilowatt-hour Generated.

Coal = 13,000 B.Th.U. per lb.
Oil = 60s. per ton.
(Steam consumption based on 20·5 lbs. per kilowatt-hour for full load, including auxiliaries.)

size seem to be practically equal to those of oil-engine installations, the savings shown will not be appreciably affected by the charge for (1) interest and depreciation, which remark likewise holds good for (2) management, etc., which can be considered a constant for the three types of plants.

Charge (3) will show an additional saving, due to the less land area required for an oil-engine plant, but in the large majority of cases to be compared this will probably not be an important factor.

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Referring again to Fig. 11, it should be borne in mind that the savings indicated are based on comparisons with high-class economical steam plant using coal of approximately 13,000 B.Th.U. per lb. Should the steam consumption be higher and the B.Th.U. of coal lower than these made use of for curves in Fig. 11, the savings will be considerably greater, as shown on Fig. 13, where—

Steam consumption	26 lbs.
Coal	11,000 B.Th.U.
Oil cost	6os. per ton.

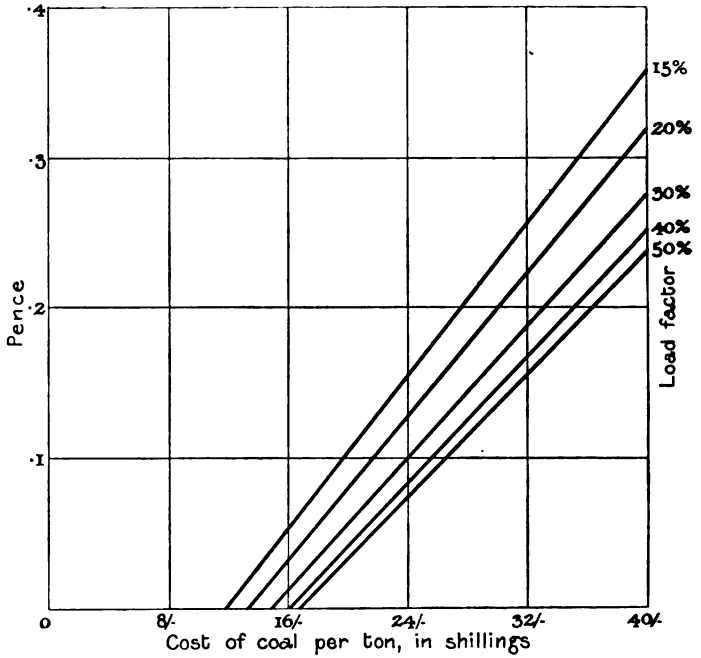

FIG. 12.—Gas *versus* Oil = *Savings* Effected by the Oil Plant in Works Cost per Kilowatt-hour Generated.

Coal = 13,000 B.Th.U. per lb.
Oil = 6os. per ton.

(*c*) *General.*—The above results show that the internal combustion oil-engine working on the Diesel principle possesses advantages both from a technical as well as a commercial standpoint, which will make this type of prime mover a most important factor in future central station practice.

Its limit of application depends primarily upon relative fuel costs, which for Great Britain would mean that it probably cannot compete with steam or gas engines in the immediate neighbourhood of coal

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centres; but as these cases, after all, are restricted in number, a very large field seems open for the consideration of this type of oil engine. For colonial and foreign work where coal costs are high, it undoubtedly possesses overwhelming advantages.

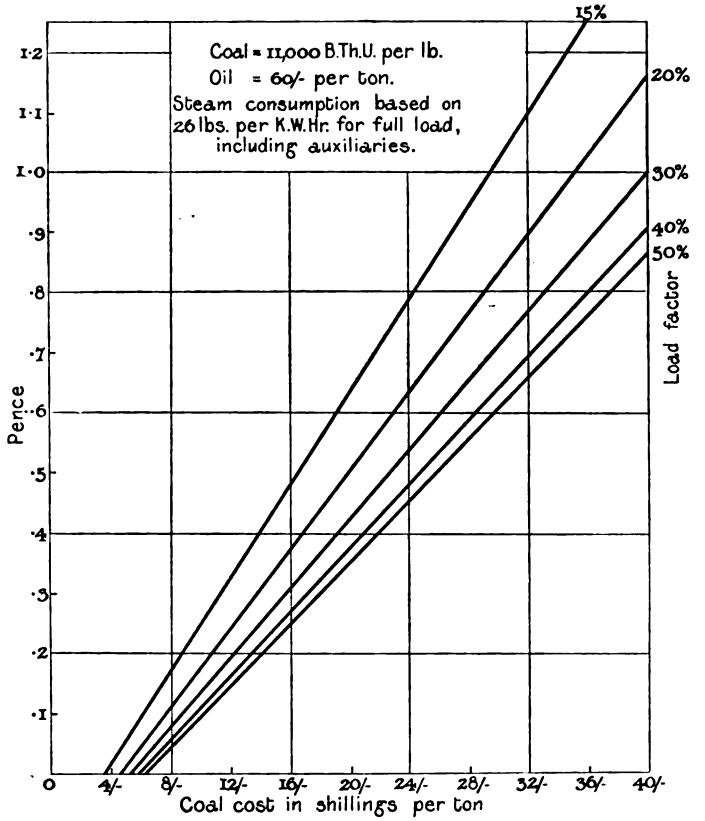

FIG. 13.—Steam *versus* Oil—*Savings* Effected by the Oil-engine Plant in Works Cost per Kilowatt-hour Generated.

COMPARISON OF CAPITAL AND OPERATING COSTS OF SUB-STATION DISTRIBUTION *versus* LOCAL OIL-ENGINE PLANTS.

The superior economy within certain limits of fuel costs of the Diesel engine in central station work leads to the question whether a Diesel plant can successfully compete with, or rather, take the place of sub-station distribution, especially in connection with very large systems where generating costs are low.

The divergence of conditions governing sub-station practice is much

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greater than that for central station work, and therefore a general basis of comparison with oil-engine stations proportionately more difficult.

While in sub-station practice the costs of converting machinery per kilowatt are generally confined within well-established limits, this is not the case with the transmission system, the cost of which, apart from distance, may vary considerably, depending upon the type, size, method of laying, nature of pavement; etc.

Available site is another point of importance, which may considerably influence capital costs.

Suppose we take the case of a large distributing system in London,* having an outlying central station feeding ten sub-stations, each sub-station having the output and size of the oil-engine plant considered in the foregoing.

Transmission by means of high-tension underground cables, each station being debited with 5 miles of duplicate cable. Conversion by means of transformers and rotaries.

Maximum load on each sub-station, 1,600 k.w.

Loss in transmission and conversion, 14 per cent.

Capital Costs.

Sub-stations.—If the sub-station plant is worked out on the assumption that the overload capacity of the converter sets is made use of to the extent of 15 per cent. in excess of the Diesel engine at the times of maximum demand, the resultant normal rating of the running machinery required $= \frac{1,600}{1{\cdot}15} = 1,400$ k.w., and allowing 25 per cent. for spare, the plant installed at each sub-station would be 1,750 k.w., as against 2,000 k.w. of oil-engine plant.

	£ per Kilowatt Installed.
Plant	4·75
Building	2·00
Land	3·25
	£10·00

Total for 10 sub-stations, £175,000

Transmission.—5 miles × 10 × £3,000 per mile of duplicate cable = £150,000

Central Station.—Assuming a diversity factor of 1·25, the capacity of the central station would be as follows:—

	Kilowatts.
Running machinery	12,750
Plant installed (allowing 20 per cent. for spare)	15,500

* Some of the following figures for capital and operating costs were based on figures given in the paper by Mr. J. H. Rider, on "The Electrical System of the London County Council Tramways," read before this Institution (*Journal of the Institution of Electrical Engineers*, vol. 43, p. 235, 1909).

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If the cost of the central station is taken at £20 per kilowatt,* this including £6 for buildings and £2 for land.

Total for central station, £310,000.

		£
Total Costs.—Machinery		269,000
Buildings and works		128,000
Land		88,000
Transmission		150,000
		£635,000

OPERATING EXPENDITURE—WORKS COST.

Sub-station.—Pence per Unit of Sub-station Output.

	Sub-station Load Factor.		
	17·5 per Cent.	33 per Cent.	52 per Cent.
Oil, waste, stores	0·005	0·004	0·003
Salaries and wages	0·070	0·055	0·040
Maintenance and repairs ...	0·025	0·020	0·015
Total per unit	0·090	0·080	0·060

Central Station.—Pence per Unit of *Central Station Output.*

	Central Station Load Factor.		
	25 per Cent.	49 per Cent.	76 per Cent.
Coal at 14s. per ton	0·305	0·230	0·200
Oil, waste, water, and stores ...	0·010	0·008	0·007
Salaries and wages	0·050	0·035	0·028
Maintenance and repairs ...	0·055	0·043	0·037
Total per unit	0·420	0·316	0·272

* Mr. Rider's figure for Greenwich Station is given as £23·63 per kilowatt.

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Total combined.—Pence per Unit of *Sub-station Output.*

	Sub-station Load Factor.		
	17·5 per Cent.	33 per Cent.	52 per Cent.
Pence per effective unit	0·580	0·447	0·376

Interest and Depreciation.—If 5 per cent. be the interest and if depreciation is charged at the average rate of—

	Per Cent.
Machinery	6
Buildings	2
Cables, etc.	3

the following would be the additional charge per effective *kilowatt-hour output of the sub-station* :—

Load Factor.	17·5 per Cent.	33 per Cent.	52 per Cent.
Pence per Unit—			
Interest	0·310	0·162	0·104
Depreciation ...	0·226	0·118	0·076
Total	0·536	0·280	0·180

Conclusions.—If in connection with the ten local Diesel plants we allow £5 per kilowatt installed as the value of land, the total capital involved, based on 2-cycle engines, would be £560,000 as against £635,000 for the central station sub-station scheme.

The table on page 27 shows the difference in total operating expenditure per effective unit including capital charges (management, rates and taxes, etc., not included).

Judging by these results it is evident that under the above assumptions the local Diesel plants can be operated cheaper than a system of a large outlying central station distributing power by means of converting sub-stations.

It would seem therefore that engineers whose central station capital and operating costs are approximately equal to or higher than those assumed above will, therefore, find it well worth their while to give the Diesel engine due consideration in connection with either extensions to existing central stations, or in cases where it is a question of supplying power at points so far removed from the main station as to involve heavy additional capital and operating expenditure in connection with transmission and conversion.

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Cases may arise where conditions and considerations vary appreciably from the assumptions made use of in the foregoing calculations, but it is hoped that the method of arriving at the above results shows sufficient detail to permit of special problems being easily solved.

	Local Station Load Factor.		
	17·5 per Cent.	33 per Cent.	52 per Cent.
A. Central station sub-station—			
1. Works cost—coal at 14s. ...	0·580	0·447	0·376
2. Interest and depreciation ...	0·536	0·280	0·180
Total	1·116	0·727	0·556
B. Diesel plant—			
1. Works cost—oil at 50s. ...	0·396	0·338	0·303
2. Interest and depreciation ...	0·500	0·267	0·169
Total	0·896	0·605	0·472
Difference in favour of Diesel plants ...	0·220	0·122	0·084

The author takes this opportunity of thanking those who have assisted him by placing information at his disposal to enable him to work out the above comparisons.

Discussion.

Mr. J. H. Rider: This interesting paper, following so closely after that of Messrs. Andrews and Porter, shows the amount of attention now being given to the problem of the internal combustion engine, and the information which the author gives that the Charing Cross and Strand Company are putting in engines of this kind shows that they have at any rate a future before them. I am not, however, quite convinced that the time has arrived for me to advise the London County Council to scrap its power house and sub-stations and to put in Diesel engines in sub-stations. Before attempting to deal with any of the figures the author has given, I wish to ask him if, in his reply, he will explain one point which is a question not of cost but of description, where he refers to the variations in the speeds of oil engines. I do not understand this expression, "a speed variation of $\frac{1}{160}$th," because it is usual in talking about speed variations to speak of the percentage variation of the angle of velocity, and I do not know how he has estimated the amount. Mr. Pfeiffer has done me the honour to refer Mr. Rider.

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Mr. Rider. to some figures in my paper. On page 590, in making comparisons between the costs of a power station with sub-stations and the cost of Diesel engine sub-stations, he gives the cost of ten sub-stations as £175,000, based upon figures which I gave of the Shoreditch sub-station. He takes the plant as costing £4·75 per kilowatt; building £2 per kilowatt, and land £3·25 per kilowatt. In my desire to be above suspicion in the figures which I gave, I took the most expensive sub-station we have on the whole system. I did not want anybody to say I was giving figures of sub-station costs which were very much lower than figures we had really paid. But the figures given here are actually the very highest, and the land at £3·25 per kilowatt refers to a site that cost £10,000. We have sub-stations quite as large on land that cost only £825, in fact the average of the whole of our sub-station sites is only £4,000 and not £10,000. So that, as regards the land—and I could give a similar explanation with regard to the building—the author has gone quite astray in taking my figures as his basis on which to make out the costs of his sub-station scheme. Then on page 591 the author gives the cost per unit of sub-station output. I am only able to deal with the figures in the middle column, those for 33 per cent. load factor, because they happen to coincide with my own experience here, and are relative to the figures in the column below of 49 per cent. load factor for the generating station. I do not know which sub-station the author had in his mind when giving the operating costs per unit as 0·08d. I can give figures based on the whole of last year's working. They are not hypothetical figures at all; they are, for oil, waste, and stores for the same load factor, 0·001d., and not 0·004d.; salaries and wages, 0·041d., and not 0·055d.; maintenance and repairs, 0·007d., and not 0·020d., making a total of only 0·049d. per unit for operating the sub-stations as against Mr. Pfeiffer's figure of 0·080d. The author has not taken any of these amounts from my paper; they are figures which he must explain himself. Then in dealing with the cost per unit of central station output, he quotes the first three items from my paper —that is, coal, 0·23d.; oil, waste, water, and stores, 0·008d.; and salaries and wages, 0·035d.; but he does not take the figure which I gave, which was taken from actual results, of 0·018d. for maintenance and repairs. He takes instead a hypothetical figure nearly three times as large, viz., 0·043d. I do not know where that comes from; it does not come from my paper. If you put the correct figures in, the total per unit of central station output on a load factor of 49 per cent. comes to 0·291d., and not 0·316d., which the author gives. In making comparisons of this kind for the purpose of showing the relative cheapness of a particular method of working, one has to be very careful with the figures. As my figures have been quoted, I am bound to explain that they were figures for the first half of the power house, and, as will be apparent to those who know the station, they were taken over a period during which the load was rapidly rising—that is to say, we had a much heavier load at the end than at the beginning. I am able to give some new figures based upon the actual costs since the 1st of January last, when our

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load has been very much more uniform. Instead of the cost per unit being 0·291d., the correct figure is only 0·261d., and the coal has gone down from 0·23d. per unit to 0·197d., a result largely due, I may say in confidence, to the exceedingly good working of our turbo-generators. On referring to the author's table on the last page, where he draws his comparisons between a central sub-station scheme and a Diesel oil engine sub-station scheme, it will be seen that in the middle of the column for a 33 per cent. load factor he gives a difference in favour of the Diesel engine of 0·122d. per unit, quite a big figure on a large output; but if we apply the corrections which I have just given and further modify his figures by raising the cost of oil from 50s. to 60s. per ton, the price which he gives elsewhere in the paper as being about the usual price in England, it will bring his figures up from 0·605d. to 0·641d., and my figure at the top comes down from 0·727d. for steam to 0·634d., which entirely transfers the advantage to the steam central station as against the Diesel engines. It is usually said that figures can prove anything, and I do not want to labour the point, but I wish to make it quite clear that mine are figures which have been obtained in actual practice at steam-driven stations, whereas the figures given here for Diesel plant are hypothetical. We have not any details of the prime costs, but only a lump sum per kilowatt. We are not informed of the actual running costs of any single job; there is no name given of any case where the oil engine has been worked. I want to know whether the author seriously thinks that a Diesel oil-engine sub-station scheme is a practicable one in a large city. He has taken the costs, and he has put down so much per kilowatt for the land. It is one thing to buy a piece of land in a city to put down a motor-driven sub-station, where your plant is quiet and no complications arise. It is quite another thing to buy a piece of land to put down an oil-engine sub-station where, as you will see from Fig. 3, you have to use not only oil tanks, but water-cooling towers, and silencers for getting rid of the noise from the exhaust. All those things increase the cost of the land and the trouble of working the plant. I should like the author in his reply to tell us something about the water used for the engines. He told us that it is necessary to cool the cylinders, and there is a cooling tower shown in Fig. 3. How much water is required? Does it evaporate largely from the towers? What temperature does it get to? and is it a nuisance in the neighbourhood? The only other point, I think, is with regard to the small overload capacity of these Diesel engines, and in making comparisons between a Diesel sub-station and a motor-generator sub-station that must be taken into account. The author talks about a 15 to 20 per cent. overload capacity. Our sub-station machines have from 50 to 100 per cent. overload capacity, and they often have to work at it for hours together. That must be taken into account in making any comparisons, and it is a most important factor in the satisfactory operation of a big system.

Mr. Rider.

Mr. W. B. Esson: Many comparisons are being made at the present time between oil, gas, and steam engines for electricity generating

Mr. Esson.

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Mr. Esson. works. Some two years ago I had occasion to go into the subject myself, with a view to determining which was the best, not for a central station, but for factory driving on a large scale. At the current prices of fuel for plants working on suction gas, Mond gas, steam, and oil, it came out that for 500-H.P. sets a triple-expansion condensing engine with superheating beat all the other methods. Mr. J. F. C. Snell in the paper he read a year ago at this Institution, adopting the same line of argument, came to a similar conclusion. On the whole, steam was the most economical, and the others came afterwards. As regards the size of the Diesel engine, it is quite true, as the author says, that large sizes were not available until recently. Only three years ago Messrs. Sulzer, who are makers of the Diesel engine abroad, constructed their first 300-H.P. engines, of which I purchased two on behalf of the Hong Kong Electric Company for their central station there, as they were giving up some of their older steam engines and putting in Diesel plant in their place. These engines have been very satisfactory, and I can give you the results of their working. They are 3-cylinder engines, having a 4-stroke cycle and running at 160 revs. per minute. They are coupled to 200-k.w. alternators having a frequency of 75 cycles per second, with flywheels to reduce the cyclic irregularity to 1 in 300. I may say that the flywheels are of cast iron. The alternators have not been working in parallel yet, so I cannot tell you whether the cyclic irregularity is low enough for the frequency of 75 or not, though from calculation it would appear to be all right. The switchboard arrangements are such that we can bunch groups of feeders on to any alternator direct, or we can run the alternators in parallel just as we please, so it will not matter very much whether they are run in parallel or not. The oil consumption has been measured over a considerable period, and it comes out at 0·72 lb. per unit generated with an average load of 125 k.w. on each machine. That is the average load, so they are probably working between $\frac{3}{8}$ and $\frac{7}{8}$ of full load. The author says a good deal about thermo-dynamic efficiency, but as a matter of fact, the thing we want to find out is what the fuel costs us at one end of the system, with all the costs intervening along the system, and what we get in units at the other end. That is the real point. It is quite true that in the oil engine there are no standby losses, and provided that such engines as are running in the station are fully loaded, the oil consumption is practically independent of the load factor. But whether a good or bad case is made out for the oil engine as compared with the steam engine depends on the amount of the standby losses assumed. There is with the steam-engine station a certain fuel consumption which is a variable depending on the number of units generated, and a constant fuel consumption which is practically independent of the number of units generated. According as this constant is large or small, a bad or good case is made out for the steam engine. I think the author has greatly exaggerated the standby loss as shown in the curve, Fig. 6. If one redraws the curve, and instead of the fuel

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Mr. Esson.

consumption per unit according to the load factor, shows the total consumption of fuel for particular load factors, we get the extraordinary result, that for no load at all in the station, when the fuel is simply used to make up the standby losses, its consumption is no less than one-third of the total fuel which would be used when the station is running at a load factor of 50 per cent. Of course that is absurd; these standby losses are far too large. Putting it in another way, the author's curve redrawn shows that the standby losses use up half of the fuel that the station would use when running with a load factor of 25 per cent. Any station engineer knows that the standby losses in a steam station are nothing like that, and such figures vitiate in my opinion the whole of the author's arguments as regards the comparison between the oil engine and the steam engine. These are the arguments of a special pleader, but I do not think they can be accepted. There is a very great danger in arguing generally on this question, and I think each individual case should be taken up and considered on its merits. A case came before my notice only recently in which I had to advise upon some plant for Calcutta. In the East oil is cheap and coal is dear, and the people whom I was advising determined in any case to use oil. But the question arose as to whether we should have ordinary oil engines or Diesel oil engines, the latter being, of course, very much more economical in fuel consumption than the former, the ordinary oil engine in the case under consideration using 87 tons of oil per annum whereas the Diesel engine used only 37 tons. Notwithstanding all this, it came out that it was cheaper to use the ordinary oil engine and 87 tons of oil per annum than the Diesel oil engine with 37 tons per annum because the saving in fuel did not compensate for the interest and depreciation on the additional capital the latter involved. Another case came before me in which it had to be decided whether suction gas or Diesel engines should be used, and the result took the same turn—namely, that although the suction gas cost more for fuel, there was not enough saving with the Diesel engine to pay for the interest and depreciation on the extra capital. How the result will turn out depends upon the hours of running. The author gives the cost of Diesel oil at 48s. a ton. One of the manufacturers of the Diesel engine in the North told me the other day that Diesel oil delivered into his works cost 55s. a ton, and near London the cost of the oil is 51s. 6d. I conclude by emphasising the point that general arguments in such cases are not of much value. The cost of fuel varies in almost every county, and therefore it is necessary to consider cases individually as they arise.

Mr. Dixon.

Mr. H. LESLIE DIXON: I have had Diesel engines in use at a small station where steam plant was originally used, coal costs having become so high that on the advice of Messrs. Handcock and Dykes it was decided early in 1906 to instal Diesel engines. The results have amply justified the change, and there has been a large saving in the fuel costs, while an increased profit has been made in spite of the

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Mr. Dixon. additional capital charges. In such a small station, generating only 170,000 units per annum, a fuel cost of 0·27d. per unit is very creditable and lower than many much larger stations accomplish with coal. The total works cost was well under 1d. per unit. With regard to the working of the engines, we have had Diesels in use for three years, and the total cost of repairs has been under 40s. At another station, with which I am acquainted, Diesel engines have been working for the last five years, and a few pounds would cover the cost of repairs, for three engines, for the whole of that time. The engine cylinders keep very clean owing to the perfect combustion, although using crude oil; indeed, there is less deposit on the piston-top than is found in the ordinary motor-car petrol engine. As a result it is only found necessary to draw pistons for cleaning once a year, valves being touched up with a little emery fortnightly. The ease of working is remarkable, and the man who drives the plant at Leatherhead is the ex-stoker, who has been taught to turn on the compressed air for starting and to oil round, and up to the present there has been no trouble whatever. Quick starting is a great feature, and we have got away a 120-H.P. set and put it on full load in 45 seconds; that is a feature which is most valuable in central station work. Should it be necessary to shut down a set for a hot bearing it is possible to get a second engine away on the load before the first has time to slow down. The engines at the stations referred to are not of English manufacture, but were built by Sulzers; the workmanship on the engine is very good. There are two engines, each of 120 B.H.P., direct-coupled to direct-current generators.

Mr. Handcock. Mr. H. W. HANDCOCK: As we were probably among the first to use Diesel engines, or at least to rely on them entirely for small stations, I thought possibly it might be of interest if we had a few figures looked up, going back for some years, to see what the results were that had actually been obtained, not on test, but on every-day working. I should say incidentally, that I can quite bear out the very good report that Mr. Dixon has given us of the working at Leatherhead. Here are some of the actual figures: In 1905, when the steam plant was at work, the cost of fuel per unit generated was 1·044d. and the total works costs 1·933d. In 1906 a mixed system was in use, so that the figures for that year are not worth very much. In 1907, when the Diesel oil engines had been installed, the cost of fuel had gone down to 0·3245d. and the total works costs to 1·238d.; while in 1908 the cost of fuel per unit generated was 0·2900d., and the total works costs 0·762d. So that, despite metallic filaments, we are fortunately able to show our shareholders quite a comfortable little dividend. During those periods the average cost per ton of oil delivered in tanks at the station at Leatherhead was, in 1906 63s., 1907 66s., 1908 70s., and 1909 66s., so that the price is now coming down a little. There is one point in that connection I should like to mention. When we first started to use Diesel engines, oil was in the neighbourhood of 40s. a ton, and I do not think anything has unsettled us, and possibly others, more than the terrible fluctuations that we get in the price of oil. Some time ago we made

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inquiries in the City, and we were told the price might go up to 90s. a ton; others suggested it might come down to 35s. If those who are interested in the oil trade could only see their way to give us a supply at a fairly even rate and make it a fairly regular commodity, I am sure the Diesel engines would be used much more extensively than they are at the present moment. I will turn next to a station which was turned over entirely to Diesel engines somewhat before Leatherhead—I allude to Hindhead. That is quite a small station, and fuel is very expensive there because of the distance it has to be carted, the altitude of the station being nearly 900 ft. In 1904, with coal, the cost of fuel per unit generated with non-condensing plant, water being scarce, was 1·67d.; in 1906 for the Diesel engine it had gone down to 0·432d., and in 1907 to 0·356d. Taking it altogether there is no doubt that in small stations we have derived very great advantage from the use of Diesel engines. At the same time, I think it is only fair to say that in our experience they want more skilled attention than a steam engine. On the other hand, the repairs, if the engines are properly looked after, are practically *nil*. I may say, as the paper deals with gas as well as with oil, that we have obtained equally economical results with the gas engine. There is no doubt that small suction plants can give an extremely good account of themselves. I am inclined to think that in the future the race between the two will be a very close one indeed. The capital outlay on Diesel oil engines, as compared with gas engines, seems rather high, and that is a matter we must take into consideration. In laying out a plant for a company, the engineer naturally settles the depreciation fund in accordance with what he believes will be the life of the engine. If, on the other hand, he is acting for a local authority, where the period of the loan is abnormally shortened, it may pay him to instal the gas engine as being cheaper, although under certain conditions with a dear fuel it may cost somewhat more to run it.

Mr. Handcock.

Mr. H. M. SAYERS: There is no doubt at all about the extreme efficiency of the Diesel oil engine, and one of the features of the tests made by many good authorities is the remarkable consistency of those tests. From 0·42 to 0·46 lb. per B.H.P.-hour covers the range of the tests at full load. Small engines are almost as economical as large ones. That is an advantage not shared by the steam engine, or to nearly the same extent by the gas engine. Nevertheless, the Diesel oil engine has not made the progress which might have been expected from its proved superiority. It is interesting to consider why it has not done so. No doubt the natural conservatism of engineers and other people has had some influence, but it is not the only reason. The difficulty of getting information about the Diesel engines has been rather serious. For some reason or other the Diesel Company have never given information promptly; they seem to look upon the Diesel engine as a sacred thing which is not to be spoken of lightly. Its dimensions and weight must not be given forth from the sanctum without very careful inquiry and consideration. This is an attitude which the ordinary engineer does not like. He cannot understand

Mr. Sayers.

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Mr. Sayers. coyness on the part of a company. The next item is the high price of the engines. The author gives prices which, so far as I can check them, are a little too low. I should say that for the sizes he mentions £20 per kilowatt is the correct figure; that is an addition of 25 per cent. to the price of steam plant which he quotes. It is true that there is a saving on the buildings, and that no boilers or gas producers are needed. But the purchaser of the plant makes no saving. He does not get boilers or gas producers, but he has to pay the price of them to the engine builders. It looks as though the prices of the Diesel engines have been carefully worked out to make the total cost of engine and generator up to the price of a high-class steam- or gas-engine plant complete. I venture to suggest that that is a mistaken policy. The most important thing, however, which has delayed the use of the Diesel engine is the uncertainty as to the supply and price of oil. In my own experience the price has ranged from 42s. to 75s. a ton. That is annoying and disturbing. One cannot confidently recommend the choice of a plant for which the vital material varies so much in price. He is sure to hear of it if the price goes up and expectations are not realised. Is it likely that that uncertainty will continue? I venture to think not. In the first place, the Diesel patents will run out before many years have passed; there will be a larger number of Diesel engines used, and with that larger number I imagine the number of sources of supply of oil will increase. It may not be generally recognised that a great amount of fuel oil could be produced in this country, if it was worth while, from materials which exist in great abundance, small coal for example. If bituminous coal is distilled at a low instead of a high temperature it gives off a small amount of gas and a large amount of oil. I believe that average bituminous coals will give off about 70 gallons of high-class fuel oil per ton. That is about 1 ton of oil per 4 tons of coal. If 1 ton of oil will do the work of 4 to 5 tons of coal, the carriage of the oil will be much more economical than the carriage of coal, and the total cost at the end of a fairly long railway haul may be less than that of the equivalent coal. Oil pipe lines from the coal-pits to the big towns may assist materially in solving the power distribution question. The amount of coke left behind from 4 tons of bituminous fuel is about 2 tons; there is also a little gas, and the gas and some of the coke would provide the power for the pits, the heat for distilling, and so forth, and probably leave some over for sale for other purposes. Then, again, lignite will produce good oil. I believe there is a very large lignite oil industry in Germany. From some figures given in Mr. E. T. Mills's book on "Destructive Distillation," I find that from 60 to 65 per cent. of the lignite is converted into oil products, of which about three-quarters consist of oil suitable for fuel for Diesel engines; the rest is pitch. Peat can also be distilled, and will give out a fair amount of oil. There was at one time a paraffin oil industry in Ireland using peat as the raw material. That was nearly half a century ago, but the trade was killed by shale oil and American petroleum. Speaking of shale reminds me

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Mr. Sayers.

that the shale which is generally used by the Scotch oil producers is not the shale which gives the greatest quantity of oil per ton. Mr. I. T. Redwood says, "Some of the shales that show the smaller yields of crude oil are often far more valuable to the companies than the shales that give twice or thrice the quantity of crude oil. This is due to the fact that the crude oil resulting from shales or coals that give a large yield generally contains very little paraffin wax, but large amounts of illuminating and lubricating oils, the latter of low specific gravity and poor lubricating quality." But it would be very good fuel oil; so that if there is a demand produced by the wider use of these engines it appears to me there are ample sources in this country, independent of the artificially manipulated mineral oil market.

Mr. Andrews.

Mr. LEONARD ANDREWS: The author has been good enough to refer, on page 581 of his paper, to the table of overall thermo-dynamic efficiencies contained in our recent paper on "The Use of Large Gas Engines." He states: "It will be found that the curves shown in Fig. 6 will pass very closely the points representing the average results of 20 steam plants and 8 gas plants." I have had a diagram prepared showing the relation of the author's curves to the actual thermo-dynamic efficiencies recorded in our paper, and it will be seen that these curves do agree very nearly with the average results. I am afraid, however, that those of us who are interested in the development of internal combustion engines must face the fact that the steam-plant efficiencies we shall have to compete with will be somewhat higher than the average results that have been obtained up to the present time. In the comparison between gas and steam plants in our paper we assumed that the steam-plant efficiencies would be about 10 per cent. higher than the average efficiencies published, and in Fig. A I have now shown an amended curve 10 per cent. higher than Mr. Pfeiffer's steam curve. I think it will be agreed that this amended curve truly represents the steam-plant efficiencies it is reasonable to expect for load factors ranging from 10 to 60 per cent. in cases where continuous supply has to be maintained. Mr. Rider's result, as published in his recent paper, is shown at A. It will be seen that this is slightly below the efficiency I consider attainable, but, as he has just told us, he has already obtained better results with his new steam turbines. Some of the recorded results are higher than my amended curve; but this is, I think, due to the fact that these installations are running under abnormal plant factors, secured by entirely shutting down the installations for a certain period every day, the supply being, in some cases, maintained from other stations. Mr. Pfeiffer's gas-engine curve may, I think, be taken to represent correctly the overall efficiencies attainable with gas engines. The difference between the steam and gas curves corresponds to a saving of approximately 1½ lbs. to 2 lbs. of coal per kilowatt-hour, the heating value of the fuel being 13,000 B.Th.U. per lb. It would be instructive if Mr. Pfeiffer would complete this diagram by showing a number of actual overall efficiencies obtained in existing oil-engine stations. He has already given us a hypothetical curve for oil engines,

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Mr. Andrews.

but it would be of far greater value if he would show what relation this curve bears to actual recorded results, as I have endeavoured to do with his steam and gas curves. I find that the figure Mr. Esson has just given us of 0·72 lb. of oil per kilowatt-hour is equivalent to a thermal efficiency of 25·8 per cent., assuming the calorific value of the oil to be

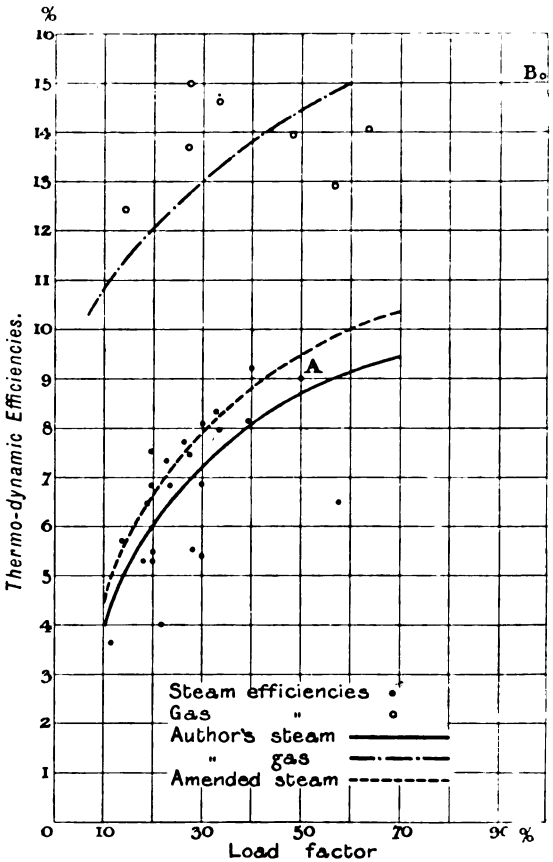

FIG. A.

18,500 B.Th.U. per lb. This agrees with the author's figure for a 17·5 per cent. load factor.

Where I disagree with the author is in his estimates of fuel costs, both for gas and steam as compared with oil. I think, in the first place, as regards steam, he has taken the price of coal much too high for an average result throughout the country. As one or two speakers have said, it is very difficult to compare these results, because the price of

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coal varies so tremendously, but I think 15s. a ton is certainly too high. The price of 25s. per ton which he has taken for the gas plant is worse still; I cannot understand why he has taken this figure. Result B in my diagram was obtained with coal costing 9s. a ton, and the other results were obtained with coal costing about the same figure. The author probably has in mind anthracite coal, but no one would think of using anthracite in a 2,000-k.w. producer plant, unless the locality was such that it could be obtained at a lower price than bituminous coal. I think 12s. per ton is an outside figure to allow as an average for either steam or gas to compare with oil at 60s. per ton. If we accept the author's figures for relative efficiencies and take the cost of coal at 12s. a ton, instead of 25s., both for steam and gas, the total works costs for a 33 per cent. load factor come down to 0·455 for steam, 0·374 for oil, and 0·348 for gas; which confirms Mr. Handcock's experience that there is little to choose between gas and oil as regards works costs. The only other remark I have to make is that, although I was very much slated a few weeks ago for talking about £14 per kilowatt as representing the capital cost of steam plant, no one has objected to Mr. Pfeiffer's figure of £24·5 per kilowatt. Mr. Andrews.

Mr. H. S. RUSSELL: The author's remark that comparatively little seems to be known about the Diesel engine in this country is hardly correct, because to my knowledge there are a number of station engineers at the present time who are contemplating their use, and a great many others who are considering them for new stations not yet put down. Although the paper refers to medium-sized stations, there is a large field for Diesel engines in this country in smaller stations, and also for light load sets in large stations which have low load factors. I do not think engineers, as a rule, have sufficiently studied the great economy that can be obtained, even in existing steam stations, by the use of Diesel engines to supplement their present plant. There were some tests taken recently at Birkdale, where there are three 90-k.w. sets, two of which are steam and one Diesel. When they ordered the Diesel set the original idea was to use it for the peak load; but having got it, they tried the experiment of running the Diesel for twenty-four hours and using the steam for the peak load. The total cost per unit, running with the steam plant, for fuel, lubrication, water, and wages came out to 1·131d., but by running the Diesel for the twenty-four hours, and using the steam sets at the peak, the total cost for the energy was reduced to 0·615d.; that is to say, running the Diesel engine for the twenty-four hours, and using the steam for the peak, in spite of the standby losses with the steam plant, they reduced their cost per unit by 45 per cent. What has been done there will be done in many other stations. On page 570, with reference to the fuel pump, the author says, "In the earlier types of engines it was customary to provide each cylinder with its own fuel pump, but of late it has been found simpler to accomplish the feeding by one pump and fuel circuit for all cylinders, thus assuring an equal amount of fuel to each cylinder at all loads." It is a fact that in the Mr. Russell.

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Mr. Russell.

early Diesel engines there was a separate fuel pump to each cylinder, but later on that was abandoned, and a single plunger pump is used by most of the Continental makers to supply all the cylinders. The practice of one British firm has been to use one pump with a separate plunger to each cylinder, and I think all will agree that equal distribution of fuel to the cylinders at all loads is much more likely to be attained with a separate plunger than by having a single plunger and depending on the thick viscous oil being distributed equally. Another advantage in working with a separate plunger for each cylinder is that owing to the way the pump of the Diesel engine works, and to the fact that the governing of it is done by varying the time during which its suction valve is open, it is quite simple to arrange a device by which the suction valve can be kept open for any cylinder, and the oil can be returned to the pump reservoir. In 3- or 4-cylinder engines one or more cylinders can be cut out by keeping the suction valve of the pump open and returning the oil. Therefore with a varying load the engine will run more economically. At Lewes with a 4-cylinder Diesel engine, when they start the Diesel engine they start up as a 2-cylinder engine, and then put the third and fourth cylinders in as the load comes on.

The President.

The PRESIDENT: How is the balance affected? Does it run steadily under all those conditions?

Mr. Russell.

Mr. RUSSELL: Yes, it runs perfectly. The fuel costs at Lewes taken over the whole average load are 0·24d. per unit, the oil at present costing 51s. 3d. a ton, so that that would correspond to a consumption of about 0·7 or 0·72 lb. per unit, the figure that Mr. Esson mentioned. There is another point that the author referred to in his paper, and that is the 2-stroke cycle engines. The author speaks of them as if they were something new. It may interest him and some others here to know that 2-stroke cycle engines were made in this country seven years ago—in fact one of them was exhibited at the Glasgow exhibition in 1901 or thereabouts—but they were found unsatisfactory and were abandoned. I think it is a mistake for the author to think that the use of a 2-stroke cycle engine will necessarily cheapen the construction of the engine. The limitation in Diesel engines, as in all internal combustion engines, is determined by the heating. It is very attractive at first sight to think that by using the 2-stroke cycle instead of the 4-stroke cycle it will be possible to get twice the power with the same size of cylinder and stroke, but really that is not so, because with twice the power the engine is generating twice the heat, and this cannot be got rid of. In comparing a 2-stroke with a 4-stroke cycle engine, it will be found that the 2-stroke cycle engine will only run at half the speed, and therefore there is no gain in cost. I should like the author in his reply to kindly confirm the figure he gave for the cyclic variation with the Daimler Motor Company's sets, because it seems to me that the variation of $\frac{1}{150}$ is rather bad for paralleling alternators. Most alternator makers in this county insist on $\frac{1}{250}$ or $\frac{1}{300}$. The author mentions on page 574 that below

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Mr. Russell.

$\frac{1}{5}$ to $\frac{1}{8}$ full load smoke from the engines comes into evidence. Our experience is that all our engines will run quite smokelessly down to $\frac{1}{8}$ or $\frac{1}{10}$ full load, and if, in addition, a device is provided to cut out cylinders by using the multi-plunger pump it is possible to go still lower. Our opinion is that the engine is not working satisfactorily unless it is absolutely smokeless; no engine should give any smoke at all from the exhaust except just for the few minutes when it is being started up. Several criticisms have been made about the author's figures. Mr. Rider said, for instance, that he considered them quite hypothetical, and that he would like to hear of some figures obtained in actual practice, and some of these have now been given. From the figures I have been able to get, I must say I quite disagree with Mr. Andrews that the author has dealt too leniently with oil-engine stations, and if he has erred with the Diesel plants at all, he has made their costs higher than they actually are. I am collecting costs from several stations—I can only deal with small stations—and I find in the published figures of the stations which are using suction gas plants, and some of them very modern gas plants, in this country, there is not a single one which seems to be able to work at less than 2d. a unit total costs, whereas I have been able to get costs of several Diesel plants where the total costs come to 0·4d., 0·5d., and 0·6d. per unit. The author seems to think that the Diesel engine takes as much lubricating oil as a gas engine. That is absolutely wrong. In the first place a Diesel engine uses quite a cheap grade of lubricating oil. We pay 1s. 2d. per gallon for our oil, and we use the same oil for lubricating the cylinders and the bearings; and from long trials and actual experience we find that the amount of lubricating oil used amounts to only $1\frac{1}{2}$ to 2 per cent. of the fuel oil. The actual cost of those items in two small stations where they are running Diesel plant with fairly low load factors, much smaller stations than the author refers to, is as follows: Cost of lubricating oil, waste, water, and stores, 0·025 per unit in one case and 0·021 per unit in the other; whereas the author puts them down at 0·042. Then, I think, people do not realise how long the Diesel engine has been made in this country. The author refers to eleven years' experience. As a matter of fact the first Diesel engine was made in this country thirteen years ago. That particular engine was taken down last year and removed to Stockport, where it is has been re-erected and is working again. We made a careful examination of it, and found that all the parts were in excellent condition. With regard to the supply of fuel oil, Mr. Sayers seemed surprised because the price of fuel oil for the Diesel engine varied by 50 per cent., from 48s. to 72s.; but I think it is within the experience of all of us that coal prices have varied quite as much as that. If Mr. Sayers would refuse to recommend his clients to use Diesel engines because of the variation in the price of oil, he must also refuse to use coal at all because of the fear of a coal strike. His fear that the more extended use of Diesel engines will make any alteration in the price of oil seems to me unfounded. It is the fact, I believe, that the hundreds

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Mr. Russell. of thousands of horse-power of Diesel engines which are at present working in the world consume less than $\frac{1}{10000}$th part of the total oil production at present known, and as the sources of oil are being constantly extended, it seems to me that we can turn those hundreds of thousands of horse-power into hundreds of millions of horse-power without affecting the price of oil.

Mr. Booth. Mr. W. H. BOOTH: I greatly deprecate the discussion of questions respecting the relative costs of different engines, because it seems to me, as Mr. Esson has told us, that every case has to stand so much by itself that no general proposition can be put forward which will teach us anything. When we consider that there are about 350,000 H.P. of Diesel engines at work, it must be very evident to all of us that the Diesel engine is a possible competitor to be reckoned with. Some years ago I was making a test of a few of these engines. Assuming the B.Th.U. in a lb. of oil to be 19,300 (I was pretty confident that there was not quite that amount of calorific capacity in the oil), I found that the I.H.P.-hour cost from 0·29 to 0·33 lb. of oil, and on the B.H.P. the cost came between 0·69 for quarter load up to 0·449 for full load. With the full-load test giving 0·449 there was a hot bearing, so that that amount of oil seems to be pretty low. I would also remark that in all the tests I have made—and I have compared my own tests with tests made by other people—I have noticed that Diesel engines might almost be used as a clock. If a Diesel engine be put on to a brake and we measure the oil it uses, we can tell how long a time it has been running, so regular is the consumption. It is absolutely necessary with the Diesel engine that things should be in good order, because the pressures are high, and unsatisfactory working, or entire break-down may result if it is in bad condition. That is, unfortunately, not the case with the steam engine. We are all very fond of the steam engine because it will always run. I know it is often held up as a virtue in the steam engine that one has only to turn on the steam and it will turn round; but this may often be at great expense. But the gas or oil engine only runs with great difficulty when it is in poor condition, and I think that may be accounted a greater virtue still. It is a virtue, of course, in the steam engine that it will always run till it breaks down; but it is good policy that an engine should not run unless it is in a condition to run economically, and that is probably more true of the Diesel engine than any other. In one of the tests I made I noticed that the exhaust was exceedingly hot, and that the exhaust pipe was rather small. The result was that we had a considerable back-pressure, and we got something less than 31 per cent. thermal efficiency on the basis of the figure which I gave for the calorific capacity of the oil for the B.H.P. Had that exhaust *pipe* been larger I believe we should have got quite 31 per cent. In some tests in Belgium I got 44 per cent. efficiency on the I.H.P., and 31 per cent. on the B.H.P. In one of the stations of the British Electric Traction Company, a sub-station, I got from 40 to 44 per cent. efficiency for the I.H.P., and 30 per cent. for the B.H.P. Considering

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Mr. Booth.

the enormous temperature of the exhaust of the Diesel, and the large pressure at which it comes out, it has occurred to me that possibly something might be done in the way of using the exhaust in turbines, except that we know that turbines are very inefficient when worked with a back pressure. It is not possible to condense the exhaust gas from a Diesel engine so as to obtain it in liquid form, but it may be condensed in bulk. I think when turning away gas at about 900° or 1,000° F. it would be advantageous to cool the exhaust before final discharge, so as not to have such an enormous amount of atmosphere to be pushed away by the exhaust. The atmosphere is taken into the engine at ordinary atmospheric volume, and it is exhausted at more than double that volume, and that means a considerable amount of work. I went into the figures, and I found that there might be about 3 per cent. saved by cooling the exhaust. Recently I went into the question of using oil engines for an installation of 1,500 H.P., and comparing the cost in rupees of coal and oil I came to the conclusion that the Diesel engine would be more efficient—that is, it would be cheaper. The unfortunate part of the matter was that steam was required; but I came to the conclusion that there would be economy, even if we had to put down a steam boiler, to give steam for certain operations. Mr. Sayers referred to the question of obtaining Diesel oils from different materials, but he omitted to state that Kimeridge clay contains a considerable amount of oil, pitch, paraffin, and various other hydrocarbons. For some time there was a manufactory at Poole, where a considerable amount of paraffin wax and other hydrocarbons were made. Then there is a very small area in this country where there is a bed of lignite, which I have proved to be over 60 ft. in thickness, and I believe that this lignite would be found to be full of hydrocarbon. It is also full of sulphur, so that that would decrease its use as Diesel engine fuel. Reference was made by one speaker to the amount of water necessary for cooling the Diesel engine. That is a matter that can be easily calculated, because about three-tenths of the total heat passes into the water-jacket. There is one point I should like to ask the Diesel Company, or anybody who is interested in the Diesel engine, and that is, Why cannot we apply gas to the Diesel engine? It would be a very simple matter to compress gas and use it as a fuel in the Diesel engine, spraying it in with air as the oil is sprayed in. I believe, originally, Diesel's intention was to use not only oil, but also gas, and even solid fuel. One cannot see very much good in using solid fuel owing to the gritty nature of the products, but I see no reason why the Diesel principle should not be applied to gas. Another speaker referred to the great difficulty of obtaining the dimensions of the Diesel engine. I have had no experience of that particularly myself, but I have had a good deal of difficulty in getting dimensions from makers of internal combustion engines generally. My experience is that the internal combustion engine is extremely modest about its internals; it will never give one any dimensions.

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Mr. Dowson.

Mr. J. E. Dowson (*communicated*): As regards the heat efficiency of the oil engine, page 572, I understand that of 100 heat units put into the engine only 55 are lost in the exhaust and cooling, and that 45 are converted into indicated work, although the exhaust leaves at a pressure of about 40 lbs. per square inch. This statement, if correct, is certainly favourable to the Diesel engine, and I would ask the author to be good enough to give his authority for the figures he has put forward. Independent tests have no doubt been made, and all who are interested in internal combustion engines will doubtless be glad to have full information on this important point. I note also that the friction of the engine, pump, etc., are said to absorb only 11 per cent., whereas on page 580 it is stated that the mechanical efficiency is only 76 to 77 per cent., and I shall be glad to know if the 11 per cent. is really correct.

As to the gas plant, I understand it is of the pressure type, but there is nothing to show what the plant consists of beyond the statement that there are four or five large units (one in reserve), and one or two smaller ones. On page 574 the author says that for light loads there should be small units for the oil engine, to prevent nuisance from smoke, but no such precaution is necessary with gas power. Also with one gasholder serving all the engines there is no need to have the same number of producers as of engines. There could be three large producers (one in reserve), instead of five smaller ones, and the number of scrubbers would be reduced proportionally. The heat efficiency of the gas plant would also be higher, and the standby losses would be smaller, if there were fewer producers with fires in them. Unfortunately I cannot come to close quarters with the estimated capital outlay, as the author gives no clue as to how he arrives at his estimate of £23 10s. per kilowatt. It would be more satisfactory if he would give the items of cost for steam, gas, and oil. My own estimate of a suitable gas plant would be considerably under his. As regards the fuel for the gas plant, it is priced at 25s. per ton, but if coke or bituminous coal were used, having a calorific power of 13,000, the cost would be much less. I have a 500-H.P. plant working satisfactorily with bituminous coal, near Birmingham, where the coal costs only 8s. 6d. per ton delivered. Even anthracite in the Midlands costs less than 25s., and its calorific power is over 14,000. I think the author should make this necessary correction, and he will see that it affects several of the curves and figures he has put forward.

Mr. Pfeiffer.

Mr. Pfeiffer (*in reply*): In connection with the discussion contributed by Mr. Rider, which deals mainly with the points raised in comparing motor generator sub-stations *versus* Diesel stations, he criticises my estimates for capital and operating costs of a central station-sub-station scheme as dealt with in my paper, and which to a certain extent were based on the figures contained in his excellent paper on the L.C.C. system. In his remarks he has given us a number of interesting figures not brought out in his original paper, and which are, as a rule, very difficult to obtain.

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Mr. Pfeiffer.

Mr. Rider first points out that taking sub-station costs based on his Shoreditch figures are entirely misleading, and that instead of £10,000 for land, the average cost of all his sub-stations works out closer to £4,000. This latter figure, based on the same capacity as for the Shoreditch station, would represent as the cost of land £1·33 per kilowatt installed, and not £3·25 per kilowatt as I assumed. Perhaps Mr. Rider will see no objection to the introduction of a similar modification in my estimates of land in connection with the Diesel plants.

The interior building space of the Shoreditch station seemingly works out at 0·09 square yards per kilowatt installed. For the Diesel engines about :—

0·36 sq. yds. for 4-stroke slow-speed engines,
0·30 sq. yds. for 4-stroke high-speed engines,
0·20 sq. yds. for 2-stroke slow-speed engines—

this after making liberal allowance for free space. This space could be reduced quite 50 per cent. if land costs were very high, the oil storage tanks, water cooling apparatus, etc., being placed in the basement of the building, as is being done in the case of 3,600 B.H.P. Diesel station in the heart of London.

Allowing, for the sake of argument, a ratio even as high as 3 to 1 for land required, this would bring the cost of land per kilowatt of the Diesel sub-stations to £4 per kilowatt installed. If these modifications are interpolated, the relative capital expenditure would be £601,400 for the central station-sub-station scheme, and £540,000 for the Diesel scheme.

Mr. Rider next comments on the estimated central and sub-station operating costs, pointing out that his sub-station results are lower than the figures I assumed. While his expenditure for oil, etc., wages and salaries, will probably continue the same, it is very much open to doubt, and most improbable, if experience with other plants is any criterion, whether his maintenance and repair charges, which amount at present, after a comparatively short period of operation, to 0·007d. per kilowatt-hour, will remain at anything like such a low figure during the average life of his plant. This figure of 0·007d. represents £134 per annum on a plant having a maximum load of 1,600 k.w. and a load factor of 33 per cent., or about 1 per cent. on the total capital expended for plant and buildings, according to the estimate in the paper. It might be interesting to obtain Mr. Rider's figures on this item, say three or four years hence. He will then, perhaps, not fall far short of the figure I have assumed.

The same comments apply to the maintenance and repair charges for the central station. Mr. Rider objects to my estimate of 0·043d. per kilowatt-hour, since his present charges are only 0·018d.

These last two figures, applied to the estimates in the paper, represent 2½ per cent. and 1 per cent. respectively on the capital expended for plant and buildings. If Mr. Rider continues to keep his figures of maintenance and repair down to anywhere near his present

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Mr. Pfeiffer.

results, viz., 1 per cent. of capital outlay, with plant working at a load factor of about 50 per cent., he will be exceedingly fortunate. If he still considers this possible, he will again, perhaps, allow me to take advantage of his figure of 1 per cent. for maintenance and repairs and apply it to the estimate of works costs for Diesel sub-stations, although *relatively* I consider this figure too high. A Diesel plant, having a maximum load of 1,600 k.w. with 2,000 k.w. installed was estimated to cost about £46,000 for plant and buildings. One per cent. on this amounts to £460, which at 33 per cent. load factor represents 0·024d. per kilowatt-hour, reducing the works cost of the Diesel sub-station plant from 0·338 to 0·312 per unit.

Taking note of all these changes, adopting the actual latest results of the Greenwich station works cost, making corrections for interest on lesser land values, and still keeping oil fuel costs at the estimate of 50s. per ton—since oil, even as far back as six months ago, was contracted for in large quantities to be delivered in London for sub-station work at 48s., the comparison on the last page of the paper is not modified to the drastic extent which Mr. Rider suggests, but is as follows :—

A. *Central Station-sub-station.*

	33 Per Cent. Load Factor. d.
1. Works cost—Coal at 14s.	0·354
2. Interest and depreciation	0·271
Total	0·625
B. *Diesel Plant.*	
1. Works cost—Oil at 50s.	0·312
2. Interest and depreciation	0·262
Total	0·574

Difference in favour of Diesel, 0·051d. per unit.

It is perhaps noteworthy that Mr. Rider did not criticise the estimate for transmission costs, nor did he comment upon the efficiency of transmission and transformation assumed, viz., 14 per cent., which is most probably better than he would have been able to give for his own installation, and which in itself directly affects the power costs on the direct current side of the sub-stations. Even if his average efficiency of transmission and conversion reaches 82 per cent., the difference of 0·051d. per unit is raised to 0·064d. This would still be further increased if the maintenance and repair charges were given their probable average values, which in my opinion will be considerably higher than 1 per cent. for the steam and sub-station plant as stated above. However that may be, the difference in operating cost between the two types of installations is but small, and I can therefore quite understand Mr. Rider's reluctance to look upon a substitution

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Mr. Pfeiffer.

of his large system by local Diesel plants in anything but a sceptical way, for undoubtedly a large number of Diesel plants are more difficult to place and operate in a city than motor-generator sub-stations, due principally to external considerations. It is quite evident that the higher the load factor of the system, the less favourable the Diesel plant becomes, as compared to a transmission and transforming system, and while the adoption of local Diesel plants might be out of the question for a very large up-to-date traction system such as Mr. Rider's, it will most probably be quite the reverse, not only with new lighting systems, but more particularly in connection with the development and extensions of existing systems (whether traction, light or power) where the economy of operation is comparatively much inferior to the excellent results attained by Mr. Rider.

The Charing Cross, West End and City Electricity Supply Company, seems to be the pioneer in adopting large oil-engine plants for sub-station work. This company for the past nine months has operated a 1,000 B.H.P. station, and is about to start another of 3,600 B.H.P. Both these stations are located in the heart of London—one at All Hallows Lane, Cannon Street, the other at Drury Lane. Other instances of smaller city installations, such as a 100-k.w. (single unit) plant in Peter Robinson's building, Oxford Street, may likewise be pointed to as showing that the working of this type of plant in cities is by no means attended by serious drawbacks as regards external considerations.

Referring to the amount of water required for the engine and the temperature attained, it will be sufficient to say that the cooling water carries off about 28 per cent. of the heat. From this can be calculated very closely the amount of water required within certain limits of temperature of the water inlet and outlet.

If the average oil consumption is 0·7 lb. per. kilowatt-hour, and the oil has a calorific value of 18,500 B.Th.U. per lb., the heat carried off by the water is 3,640 B.Th.U. This last value, divided by ten times the difference of inlet and outlet temperatures in degrees Fahrenheit, gives approximately the number of gallons of circulating water required per kilowatt-hour. A rise of 75° in the circulating water would therefore require approximately 4·8 gallons per kilowatt-hour.

Mr. Rider ends by commenting upon the limited overload capacity of the oil engine. That steam engines, and also motor-generator sets, have a large advantage in this respect permits of no doubt; but after all, very large overload capacities, however desirable, are only really necessary in special cases. To operate machinery at 100 per cent. overload for two hours gives one the impression that there must be something wrong with the rating.

Mr. Esson begins his remarks by the statement that two years ago he had occasion to study the subject of the best type of plant to instal for factory driving on a large scale, and he adds that at current prices of fuel a 500-H.P. steam set, triple-expansion condensing engines, with superheat, beats all other methods. He says nothing of

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Mr. Pfeiffer.

the type of load, load factor, cost of fuel, etc., but makes an unqualified statement that steam beats both gas and oil.

Under certain conditions I have no doubt that this was the case. There is, after all, nothing so novel in his statement, for, if he studies Fig. 9 in my paper, he will see that, for a load factor of 50 per cent., steam and oil plants of the size in question are on a par, from the standpoint of operating cost, when the respective fuel costs are 10s. and 60s. per ton, or with 30 per cent. load factor with fuel at 8s. and 60s. per ton respectively, etc. It is easy to find certain districts where coal is cheaper and oil more expensive, and in such places a steam plant is undoubtedly operated cheaper than an oil plant, but it is likewise the case that in many places coal is considerably higher and oil lower than the figures given above, and in such cases the advantage is reversed. When claims of superiority are made, one ought at least to be informed about relative fuel costs, not to mention load factors, etc. "Fuel at current prices" means nothing.

I drew up my tables and curves plainly enough to permit the easy interpolation of all variable factors, such as fuel, wages, etc., so as to facilitate the study of individual cases having to deal with maximum loads approximating to 1,600 k.w. I do not, like Mr. Esson, pick out a certain size of oil engine, and without any reference to the factors involved say that it is superior to steam or gas. Contrary to what Mr. Esson believes, I am not a special pleader for the oil engine, but still a staunch advocate of the steam engine, which, for certain purposes and under certain conditions, cannot be beaten by either the gas or oil engine. My object was to ascertain under what conditions and limitations the oil engine is superior to either steam or gas, and this I have shown in the parity curves, Figs. 9 and 10. Surely it does not require much study to understand them. These curves depend, of course, primarily upon the assumed fuel consumptions, as shown on Fig. 6 of my paper, to which Mr. Esson takes such decided exception. It would have been more interesting, and perhaps more instructive, had Mr. Esson given us figures based on his experience, rather than to have indulged in a sweeping condemnation without sound argument to back it up. I do not know whether he will accept the results of coal consumption of the 20 large steam stations as tabulated in the appendix to Messrs. Andrews and Porter's paper already referred to, but until he has something better to offer I will base my reply upon these figures.

On Fig. B I have reproduced the curve of fuel consumptions, for varying load factors, which formed the basis of my calculations for a steam plant having a maximum load of 1,600 k.w., the size of units being 400 k.w. The dots represent the coal consumptions of the 20 large steam stations above referred to, the actual tabulated figures all having been reduced to the common basis of 13,000 B.Th.U. per lb. One of the two dotted lines shows the average results for 7 steam turbine stations, with varying load factors. It should be noted that the average of these 7 stations has a maximum load of 7,800; the

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lowest 3,700, and highest 22,200 k.w. If Mr. Esson will compare the dotted curves of actual results with the full line curve which represents my assumptions, he will perhaps notice that the percentage of increased consumption, with decreasing load factors, is even greater than my assumption. Mr. Esson, in his remarks, apparently overlooked the fact that this increased consumption is not only due to standby losses, but is in part attributable to the reduced efficiency of the entire plant with decreasing load factors. Perhaps this comparison will convince him that the steam engine plant did not receive the unfair treatment which he evidently thought it did. Mr. Pfeiffer.

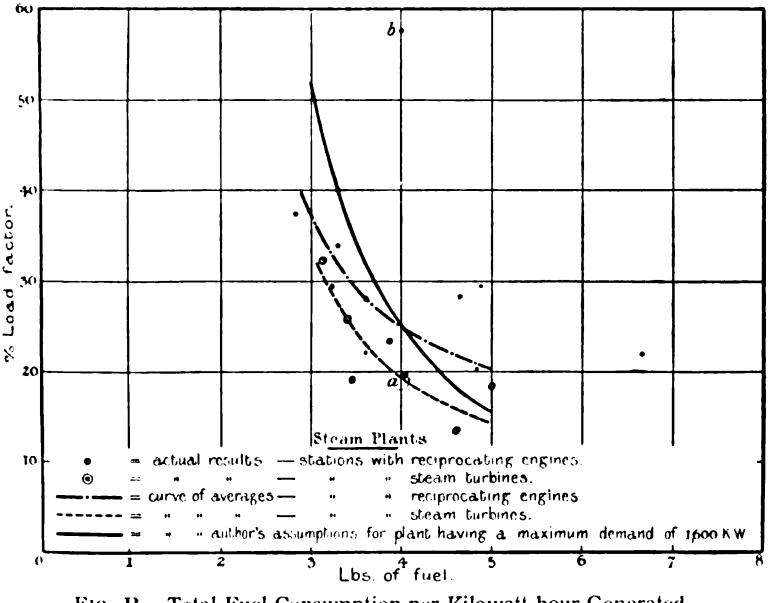

FIG B.—Total Fuel Consumption per Kilowatt-hour Generated.

a = Largest station = 22,186 k.w. maximum demand.
b = Smallest " = 1,700 "
Average of 20 stations = 7,000

Both Mr. Dixon and Mr. Handcock contributed interesting figures of the running of small Diesel stations, and the former has been good enough to give me further details of his operating costs, which will be found in the table at the end of this discussion. The good results obtained from these stations confirm the opinion that a small Diesel plant is worked almost as cheaply as a large one, as regards fuel.

Several speakers referred to the uncertainty as to the supply and price of oil, Mr. Sayers pointing out that the price has ranged between 42s. and 75s. per ton. No doubt this has been a disturbing factor, which has to a certain extent retarded the more general use of the oil engine, but I am one with him in his optimistic view that as the

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Mr. Pfeiffer.

number and size of Diesel engines increase we shall see a more settled condition in this respect. As pointed out by Mr. Russell, considerable price fluctuations even in coal, principally due to strikes, are not entirely unknown, and will, if anything, become more pronounced and frequent as labour increasingly asserts its so-called independence.

Mr. Sayers touched upon another possible source of oil fuel, viz., the distillation of coal at low temperatures, and it may not be very long before oil supply from such sources may become a commercial possibility. As a matter of fact, oil, suitable for driving Diesel engines, can already be obtained in limited quantities from a company whose process resembles that mentioned by Mr. Sayers, and who have begun to instal several plants in various parts of the country.

Mr. Andrews, in his discussion, starts by commenting upon the relative thermo-dynamic efficiencies of the three types of plants compared, and while agreeing that my average assumptions for gas plants are a close approximation to results attainable, he points out that for steam plants it would have been fairer to take efficiencies 10 per cent. higher, as per the dotted curve on his Fig. A. I quite agree with him that the modern steam plant efficiencies are higher than the average results obtained hitherto, but I still maintain that the results plotted on my curve are attained by but very few modern installations having the output and size of units which formed the basis of my comparison. I only know of one medium-sized steam plant, the results of which exceed my assumptions somewhat, and I think it will be conceded that its working is exceptionally favourable. The plant to which I make reference is located in South America, and consists of three 750-k.w. direct-current generators. The engines are of the compound condensing type, working at 155 lbs. pressure.

Superheat	250° F.
Vacuum	24 in.

The maximum load is 2,400 k.w., or very close to the total capacity of the station, while the load factor is 55 per cent. With best Welsh coal as fuel, having a calorific value of about 14,000 B.Th.U. per lb., the fuel consumption is only 2·55 lbs. per kilowatt-hour, which represents an overall thermo-dynamic efficiency of about 9·5 per cent., as against my figure of 9 per cent.

Had the comparison in my paper been based on plants of 5,000 to 10,000 k.w., permitting of the consideration of large-sized turbine units for the steam plant, then I should have felt inclined even to exceed the 10 per cent. extra allowance for the steam plant which Mr. Andrews suggests, and I believe I should not have been far wrong in allowing an additional 15 per cent., and possibly 20 per cent., in efficiency for such plants, working under good conditions of load.

Mr. Andrews suggests that I should plot actual results of overall thermo-dynamic efficiencies of oil plants along with my hypothetical curve, and this I have done on Fig. C, the points being derived from fuel consumptions of several stations, as shown on the table annexed.

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Mr. Andrews evidently misinterpreted the object of Table II., page 582 of my paper, for it was never my intention to limit the comparison of the operating costs of the three types of plants to certain specific fuel costs. Mr. Pfeiffer.

At the bottom of the same page I clearly stated that the fuel costs

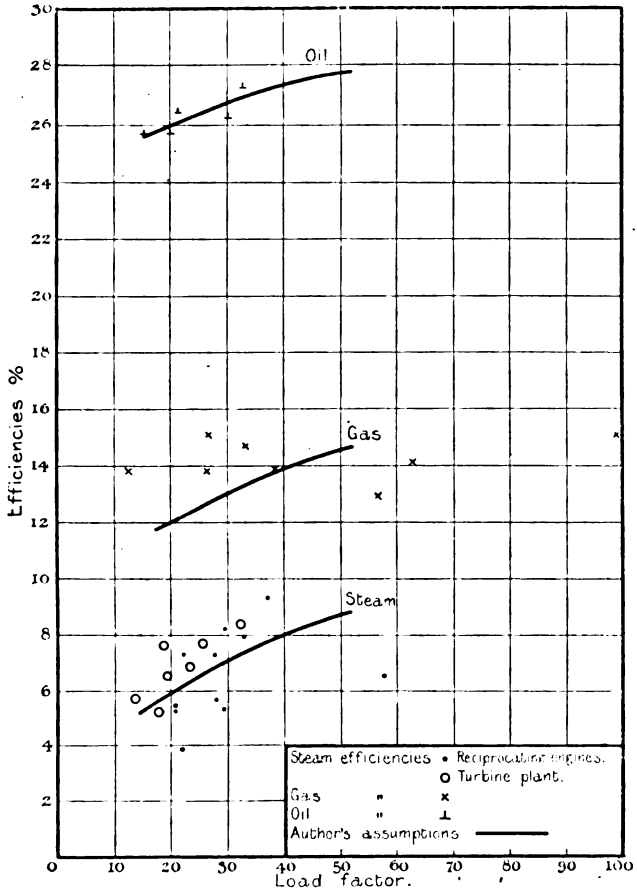

FIG. C.—Overall Thermal Efficiencies.

in the table were taken at arbitrary figures, in order to obtain the works cost curves on Figs. 7 and 8, which show the operating costs per kilowatt-hour for *any* cost of coal. Table II. was only given in detail to show how the various factors were arrived at, the crux of the paper being the parity curves on Figs. 9 and 10, which clearly show the limit of application of the Diesel engine, or, in other words, certain

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Mr. Pfeiffer.

coal costs below which the steam or gas plants would be cheaper to operate at given load factors and known costs of oil at any place. As, for example (see Fig. 9), if a steam plant works at a load factor of 30 per cent., and oil costs 60s. per ton, the operating expenditure of a steam plant would be the same as that of an oil plant, provided coal, having 13,000 B.Th.U. per lb., could be bought for 8s. per ton. If coal cost less than this the steam plant would be the more economical; if more, then the oil plant would have the advantage.

Mr. Russell, amongst other things, differs with me on a few minor details, such as separate fuel pumps for each cylinder, costs of lubricating oil, &c., which do not require more answer than to say that all the advantages which he claims for the separate pumps are likewise attainable with a single combined pump, and, while interesting, I hardly think that the difference in cost of lubricating oil per kilowatt-hour between my assumed figures and the figures he gives would influence the choice in favour of a Diesel plant. Besides, in spite of what he says about cheap grade of oil, it is generally recognised that it is a mistaken policy to try to save on this item, whether in connection with steam, gas, or oil engines.

Mr. Russell goes rather extensively into the history of the two-stroke engine, and tells us that this type of engine was tried and found wanting eight years ago, and abandoned. It seems useless to hark back to what took place eight years ago, for that is ancient history. The question is: "What is being done to-day?" Mr. Russell certainly does not seem to have kept in touch with recent developments, and therefore he may possibly be surprised to learn that personally I have recently seen in actual practical operation a 750-B.H.P. two-stroke Diesel engine, working in parallel with water turbines, driving alternating-current generators in a power station in Switzerland, and that I also saw exhaustive and very satisfactory tests on several 500-B.H.P. two-stroke high-speed sets destined for the Italian Navy. These machines were evidently not designed according to Mr. Russell's conception of a two-stroke engine, for an increased output of 80 per cent. and the same speed are attained with the use of cylinders of standard size and speed of the four-stroke rating.

Mr. Russell's remarks about the excellent condition of a Diesel engine of an old pattern and type, after working for thirteen years, is most interesting, as giving a specific case of the durability of this type of prime mover, which bears out my contention, arrived at after a thorough investigation, that from the standpoint of depreciation the oil engine is at any rate equal to the steam engine.

Amongst the many interesting remarks made by Mr. Booth, one especially struck me rather forcibly, since it touches upon a point which has interested me also, and that is whether gas could not be used in a Diesel engine instead of oil, thus taking advantage of the high pressures.

Theoretically it seems quite feasible, but whether practically it presents any difficulty I do not know. I am inclined to think, however,

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that we shall shortly hear more concerning the development of this idea. Mr. Pfeiffer.

In answer to Mr. Dowson's communication, I may say that the authority for my statement as regards the pressure of the exhaust is the indicator diagram on Fig. 1 of my paper, which is a full load card taken from a 400-H.P. engine.

Regarding the 11 per cent. he refers to, this is the percentage of the total heat in the fuel which is lost in engine friction and air-pump. To arrive at the mechanical efficiency of the set, however, this figure must be deducted from the percentage of the heat made use of by the engine, viz., 45 per cent. The ratio between 45 and 34 gives the mechanical efficiency of the engine over the air-pump.

In answer to the latter part of his remarks, I will refer him to my reply to Mr. Andrews's criticisms on the same point, since Mr. Dowson seems to have similarly misunderstood what I aimed at. He will perhaps find, after a little study, that my curves need no alteration.

OPERATING RESULTS OF DIESEL OIL-ENGINE PLANTS.

Names of Places :—	Leatherhead.	Coventry.	Birmingham.	Hong Kong.	Vera Cruz.
Total kilowatts installed	164	436	420	400	2,100
Maximum load on feeders	125	405	400	—	1,000
Average running load	—	303	—	250	—
Plant factor	—	70	50	—	—
Station factor	—	75	25	—	—
Annual load factor	15·4	29·2	21·5	—	30 p. cent.
B.Th.U.	170,000	517,005	753,100	—	1,517,240
Period covered	12 mos.	6 mos.	12 mos.	—	7 mos.
Average cost of oil fuel per ton ...	70s.	60s.	53s. 6d.	35s.	40s.
Lbs. of fuel per kilowatt-hour ...	0·71	0·695	0·703	0·72	0·71
Overall thermo-dynamic efficiency	25·70	26·700	26·400	25·70	26·20
Operating Costs—per kilowatt-hour					
Fuel	0·265	0·225	0·202	0·134	0·152
Oil, waste, &c.	0·070	0·012	0·030	-	-
Wages	0·203	0·100	0·133	—	—
Maintenance and repairs ...	0·007	0·018	0·055	—	—
Total	0·635d.	0·355d.	0·426d.	—	—

The PRESIDENT: I ask you to pass a hearty vote of thanks to the author for his interesting paper, which has given rise to such a useful discussion. The President.

The resolution of thanks was carried by acclamation.

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SOME TESTS AND USES OF CONDENSERS.

By W. M. MORDEY, President.

(*Paper received May 14, and read in London May 20, 1909.*)

The idea of using condensers for providing idle leading current to compensate the idle lagging current due to self-induction in alternate-current working seems to have been first proposed in 1891, in this country by Mr. Swinburne, and in France by Hutin and Leblanc.* The principle was not new. At the Crystal Palace Electrical Exhibition in 1891, Mr. Swinburne showed some paper condensers made for high-tension work. He also wrote and spoke on the subject.† Hardly any progress was made so far as practical applications went. And then conditions changed and the subject no longer attracted attention. There was a period when the capacity of the cables in distribution systems in many cases provided a good deal of compensation, and we find Mr. Swinburne saying in his Presidential Address of 1902, that "it is hardly worth while discussing condensers now as there is generally excess of capacity in systems, so that the current leads relatively to the pressure."

But now the growth of the motor load is making a difference, and in many cases there is a real need for the improvement of the power factor in supply systems, for various reasons, such as keeping down the loss in the mains and increasing the useful output of generators and reducing their cost. The loss in the mains is inversely proportional to the square of the power factor, thus:—

Power factor...	1	0·9	0·8	0·7	0·6	0·5
Loss	1	1·24	1·56	2·04	2·78	4·0

As to the effect on cost and output, it is sufficient to quote Mr. Miles Walker's interesting paper, read before the Manchester Local Section, on January 12, 1909, on "The Improvement of Power Factor in Alternating-current Systems," in which he refers to one case where the rating of some turbo-alternators was raised 50 per cent. owing to their being used at nearly unity power factor.‡

For the improvement of power factor two methods may be compared—the use of condensers and the use of over-excited

* *La Lumière Electrique*, vol. 40, pp. 201 and 257, 1891.

† See, for example, the *Electrician*, vol. 28, p. 227, 1892: "The Probable Future of Condensers in Electric Lighting."

‡ *Journal of the Institution of Electrical Engineers*, vol. 42, p. 602, 1909.

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synchronous motors.* The latter method is practically the only one that has so far obtained engineering recognition. I am glad to be able to give some particulars of one interesting example of its use, for which I have to thank Mr. Fedden, of the Sheffield Corporation. He has installed a specially designed motor made by the British Thomson-Houston Company. It has a capacity of 600 k.v.a., and consists of a 2-phase motor for 2,000 volts 50 ∿ with a direct-current exciter and an induction motor for starting up, all on one shaft. It is used at intervals during the day to keep up the power factor of the system and to reduce the excitation of the main turbine generators, which are in a station 2 miles away. At the present time the average day load is about 4,000 k.v.a., at an average power factor of 0·7, equal to an actual load of 2,800 k.w. The rectifier raises the power factor on an average to 0·83, reducing the apparent load from 4,000 to 3,380 k.v.a., thus releasing 620 k.w. of capacity in generators, and in cables between the two stations. These figures correspond to a load on the motor of nearly 1,000 k.v.a.

Having had occasion to use condensers for some experiments on arcs, which are alluded to later, the opportunity was taken to investigate some of their qualities to see to what extent they might be considered suitable for use on alternate-current systems. The results seem to point to such use being now within the region of practical engineering.

There are many kinds of condensers, including those in which the electrodes are separated by air or oil, but for our present purpose only two types will be considered :—

1. Paper condensers of the kind described by Mr. Mansbridge before this Institution last year, † and
2. The Moscicki type of glass condenser.

The former are made, by a continuous process, of paper coated on one side with a thin metal layer like the so-called silver paper used for packing tea. These have the great advantage that if they are pierced they are self-healing, the metal being vaporised so as to produce a space clear of metal round the fault.

They appear, however, only to have been made for low pressures, and therefore, so far as the author's present knowledge of them goes, a number of them must be placed in series for high-pressure working.

The Moscicki condensers, which are not at present being made in this country, consist of specially formed glass tubes closed at one end and coated inside with silver deposited chemically, the outside coating being sometimes applied in the same way and sometimes dispensed with altogether, the outer electrode consisting in this case of a mixture of glycerine and water, in which the tubes are immersed. These con-

* The quality possessed by such motors which makes them available for this purpose—illustrated by the V-curves connecting armature and field current—was described by the author in a paper on "Testing and Working Alternators," *Journal of the Institution of Electrical Engineers*, vol. 22, p. 116, 1893.

† *Ibid.*, vol. 41, p. 535, 1908.

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densers are said to be largely used for wireless telegraphy, for which purpose the metal coating is made very thick in order to lessen the resistance and the damping effect. They are being used in some cases abroad for power factor improvement on extra high-tension transmission lines. They seem to be very suitable for this purpose, as by the use of a suitable thickness of glass they can be made to withstand a very high voltage.

No information regarding the losses was obtainable for either of these condensers. I have therefore had some tests made of both types by Mr. Wild of the Westminster Testing Laboratory. The results obtained are only to be taken as approximately correct, instrumental difficulties introducing some uncertainty in the measurement of power in apparatus having power factors of only about 0·01. It is believed, however, that the results may be relied upon for the low-tension paper condensers within 5 per cent. each way, and for the high-tension glass condensers within 7½ per cent. each way at the highest voltages and 15 per cent. at the lowest.*

A Mansbridge condenser made for 500 to 600 volts direct current, and having a capacity of about 10 microfarads, was tested with alternate current at various pressures from 100 to 500 volts and at 25, 50, and 75 ∿.

The results of the tests are shown in Fig. 1, which gives the loss in watts per microfarad at various voltages and frequencies, and the power factor at various frequencies.

The capacity, as shown by the proportionality of current to pressure and to frequency, was almost constant. The power factor was also found to be nearly constant at all frequencies from 25 to 75 ∿. The variation of power factor with voltage was less than the instrumental errors within the limits of the tests. The curve for power factor shows the mean results for the three highest voltages. It will be seen that the loss of energy was small.

Having found the qualities of a low-tension condenser, it would seem that no difficulty should be met with in using a number of such condensers in series for high-tension work, as the conditions in each section as to voltage, loss, and power factor, will be the same when used in such a series as when used singly. The British Insulated & Helsby Cables, Ltd., who made the condenser tested, have, in answer to the author's question, suggested 500 volts per section for a condenser so made up for 10,000 volts, and state that it would occupy

* The Mansbridge condensers were tested with a wattmeter of the reflecting deflectional type. It was ascertained that the error due to the self-induction of the pressure coil did not exceed 1½ per cent. on a power factor of 0·015 at 50 ∿.

The Moscicki condensers were tested with the same wattmeter in conjunction with a 100 to 1 potential transformer. The potential transformer brought into the measurement an error of the order of 20 to 25 per cent. In order to obtain a sufficient deflection on the wattmeter, it was necessary to cut down the non-inductive resistance in series with the pressure coil to such an extent that another error was brought in of the order of about 20 per cent. This error was in the opposite direction to that involved by the use of the potential transformer. Both these errors were determined with a fair degree of accuracy, and were allowed for in the final result.

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about 2 cub. ft. per microfarad, and they think the price would be about £27 per microfarad. They, however, state that they have had no experience of condensers so made up or used. The above tests and information, however, enable a tentative comparison to be made with the 10,000-volt Moscicki condenser tested.

This Moscicki condenser consists of eight tubes, having a total

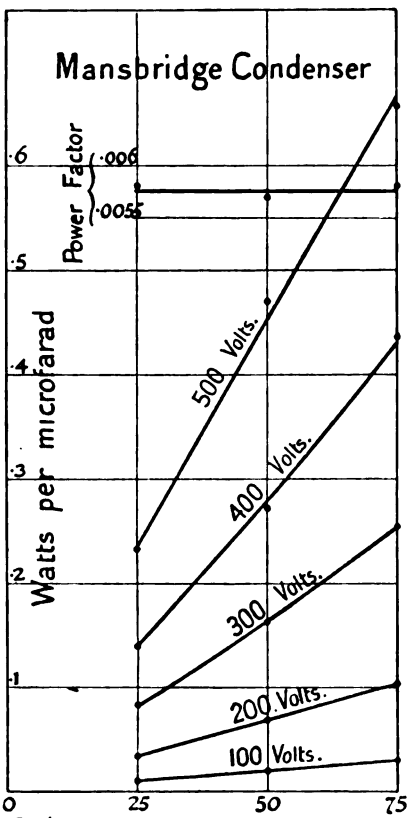

FIG. 1.—Tests of Low-voltage Paper Condenser.

capacity of 0·03 microfarad. It is intended for alternate-current working at 10,000 volts. Each tube is 2 in. in diameter and 2 ft. 9 in. long, or with connections 3 ft. 2 in.

Owing to instrumental difficulties, it was impossible to obtain the same degree of accuracy with these tests as with the paper condensers, and the range of voltage and frequency over which it was practicable to make them was also less.

As a matter of curiosity some tests were made of a set of six Leyden

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jars of ½ gallon size, having a total capacity of 0·015 microfarad. They were kindly lent to the author by Mr. Campbell Swinton.

The curves representing watts lost per microfarad on different voltages and frequencies are shown in Fig. 2 for both these glass con-

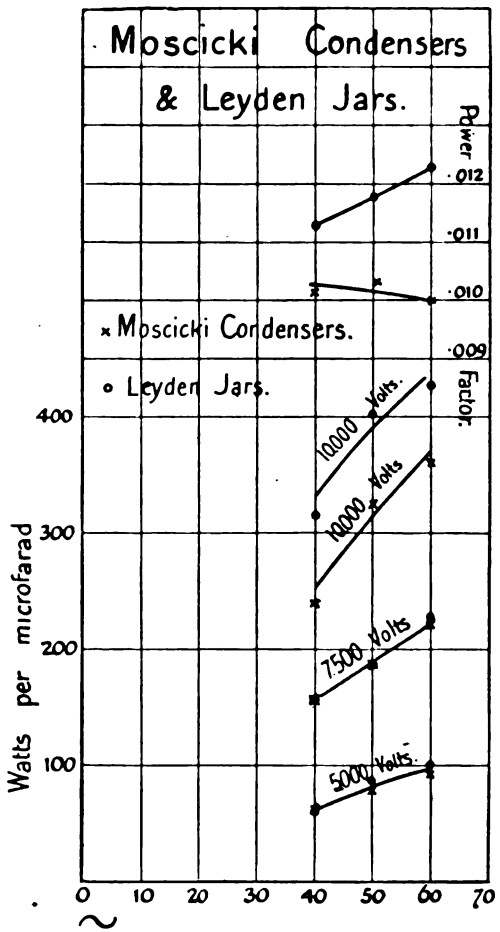

FIG. 2.—Tests of High-voltage Glass Condensers.

densers. They are similar in their character to those obtained from the Mansbridge paper condensers. At 5,000 volts and at 7,500 volts the loss in watts per microfarad in the Moscicki condenser and in the Leyden jars is the same, but at 10,000 volts there is a marked difference. There is some brush discharge in the Leyden jars from 5,000 volts upwards. The losses in the Moscicki condenser continues

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to increase approximately as the square of the voltage, while that in the Leyden jar is higher in proportion, possibly indicating an approach to the point of breakdown. It should, however, be mentioned that the jars have been used on induction coils giving a 10-in. spark, corresponding to a very much higher voltage.

The curves showing variation of power factor with frequency have been drawn from a mean of the results at the three different voltages, giving greater weight to the high-voltage readings owing to the greater degree of accuracy obtainable with them. They must be accepted with some reserve, owing to the less degree of accuracy in these tests. They show, however, that the Moscicki glass condenser

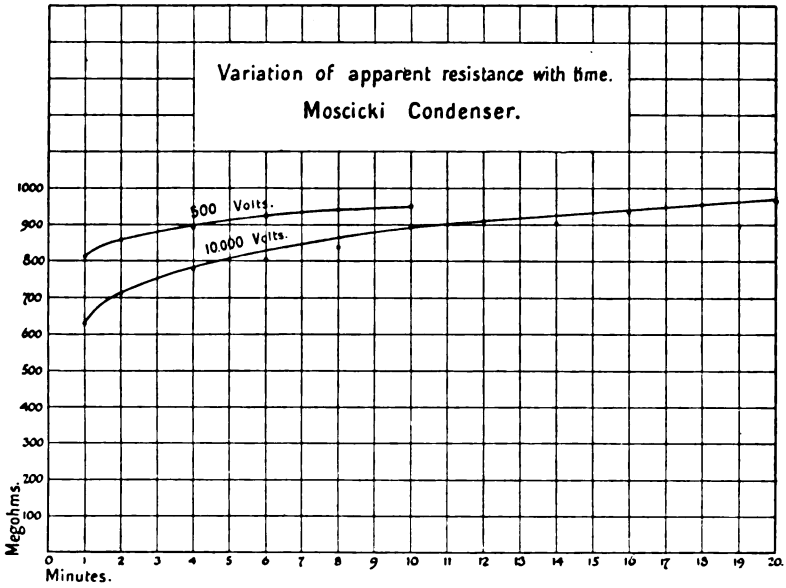

FIG. 3.

works with a loss of about 1 per cent. of the kilovolt-amperes dealt with.

It was thought to be of interest to find the variation of the apparent resistance of the Moscicki condenser and to find how its C^2R losses so ascertained compared with the energy losses found in the alternate-current test. The author was enabled to make this resistance test by using a 10,000-volt secondary battery kindly placed at his disposal by Mr. Campbell Swinton.* The apparent resistance so ascertained is

* This battery, which was made by Mr. Swinton, comprises 4,800 secondary cells, each cell consisting of a test tube 4 in. long by ¾ in. diameter, the whole being conveniently arranged for charging in a number of parallel sets of 80 cells in series. The charging current is arranged to be 8 milliamperes.

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shown in Fig. 3, readings being taken at 500 and at 10,000 volts. Unfortunately, the readings were not continued long enough to reach the steady condition, the current slowly falling—that is, the apparent resistance slowly rising—even after 20 minutes' application of the pressure.

As these curves only start with the result at the end of 1 minute, they afford no indication of what the apparent resistance would be within the time of a half-period.

It will be seen that any C^2R loss based on these resistance curves will account only for an insignificant proportion of the total losses with alternate current.

In comparing Figs. 1 and 2, it must be remembered that the power-factor, and not the watts per microfarad, is the proper basis, seeing that the loss (as well as the kilovolt-amperes per microfarad) appears to rise as the square of the pressure in any given condenser.

The proper basis of comparison is the loss in a paper condenser, made up in sections for high-pressure use in one case, against the loss in the special high-voltage glass condenser of the same capacity.

From the results shown in Fig. 1, a 10,000-volt Mansbridge condenser would lose about 190 watts per microfarad at 50 periods; and from Fig. 2, the Moscicki 10,000-volt condenser would lose about 320 watts per microfarad, the loss in the latter case being less accurately measured than that in the former.

It is satisfactory to find the losses are so small. They are respectively about 0·6 per cent. and about 1 per cent. of the kilovolt-amperes dealt with. These losses are of the same order as the magnetising losses in transformers of good design.

With such small losses as these, no difficulty should be experienced in preventing objectionable heating. Condensers lend themselves very well to arrangements giving large cooling surface. In the Moscicki type, the tubular form ensures this. The Mansbridge type can be subdivided to give any desired cooling surface.

It is perhaps a large assumption to make that condensers have reached such a stage as to justify a direct comparison with synchronous motors. It is felt, however, that a little encouragement and experience would probably enable makers of condensers to justify such an assumption, and therefore the author ventures to make the comparison.

In sub-station work, at least where motor-generators or rotary converters are used, or industrial work where synchronous motors are used, it should always be possible to arrange by over-excitation to provide a considerable amount of power factor correction at a small increase in the cost of the machinery. But there are many conditions in alternate-current supply where self-induction cannot be compensated in this way. In some cases the expense of special over-excited synchronous motors running without load may be fully justified, the Sheffield case being an example.

But the objections to the use of running machinery are very great.

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If condensers can be made to work reliably, even at the same capital and working cost as motors, they would be preferable. In any event, a comparison may be useful.

The simplest case will be to assume that either the motor or the condenser would be placed in a generating station or in a sub-station, and that the motor would not be used for any other purpose. It would be much more favourable to the motor to take the case of an over-excited motor or rotary converter doing other work, but to deal with that it would be necessary to know all the conditions.

On the other hand, it would be more favourable to the condensers to distribute them about the system. For example, they could be placed close to large motors, and switched in or out by movement of the motor switch—that would give effective correction at all loads without involving any attention.

TABLE.

Capacity in Kilovolt-amperes of Motor, or in Microfarads of Condensers required for a Load of 1,000 k.w. at various Power Factors to be Corrected to Unity or to any other Power Factor.

Power Factor of Load.	Kilovolt-amperes required at Leading Power Factor = 0.	Capacity required in Microfarads at 50 ∿.			
		2,000 Volts.	5,000 Volts.	10,000 Volts.	20,000 Volts.
0·99	142	113	18	4·5	1·13
0·98	203	162	26	6·5	1·62
0·97	251	200	32	8·0	2·00
0·96	292	233	37	9·3	2·33
0·95	329	262	42	10·5	2·62
0·90	485	386	62	15·5	3·86
0·85	620	494	79	19·7	4·94
0·80	750	598	96	23·9	5·98
0·75	882	703	113	28·2	7·03
0·70	1,020	814	130	32·5	8·14
0·65	1,165	930	148	37·0	9·30
0·60	1,333	1,065	170	42·5	10·68
0·55	1,520	1,210	194	48·5	12·10
0·50	1,732	1,380	221	55.0	13·80

The figures in column 2 represent the whole wattless component corresponding to the various power factors in column 1 with 1,000 k.w. real load. The kilovolt-amperes or capacity required for correction to any power-factor less than unity will be equal to the difference between the wattless component in the uncorrected circuit and that in the circuit after correction. Thus, to bring up a 1,000-k.w. circuit from 0·75 to 0·95 power factor requires 882 − 329 = 553 k.v.a. if a synchronous motor be used. With condensers working at 5,000 volts 50 ∿ it will require 113 − 42 = 71 microfarads.

The kilovolt-amperes required for correction are independent of frequency and voltage. The capacity required is inversely proportional to the frequency and to the square of the voltage.

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We may confine ourselves to a comparison of a case where, if any correction is to be effected, it must be by either a synchronous motor or a condenser, and will take the simplest case and assume a synchronous motor or a condenser installed at a generating or sub-station, for the compensation of a circuit requiring 1,000 k.w. at 10,000 volts 50 periods, with a power-factor of 0·8.

We see from the table on page 625 that to give unity power factor, this would need a motor of 750 k.v.a., or a condenser having a capacity of 24 microfarads.

The cost of the motor erected with foundations, switchgear, and accessories will not be less than £1,100. Such a machine would certainly not take less than 40 k.w. to run it at full load, and 20 k.w. at light load. Let us assume a mean of 30 k.w. and that it is used for 12 hours a day only. This gives a total annual consumption of 131,400 units.

The cost of a condenser of 24 microfarads for the above conditions would be about £720 with switchgear and accessories. The loss in this condenser will not be more than 1 per cent. of its apparent load—7·5 k.w. at full load. In practice, the condenser would be in sections, some of which would be switched out as the load fell, but we will assume that it is all kept in circuit for twelve hours a day. The total annual consumption would be 32,850 units.

Although there are good reasons why the energy used in such a device should be charged at the average works cost, it is preferred to take it on a lower basis of about the cost of the coal, say 0·25d. per unit.

No spare is provided in either case, and no charge is included for upkeep, capital charges, attendance, or lubrication, nor is the account in either case credited with any sum to represent the increase of useful capacity and efficiency or reduction of cost of the generating plant.

We then get the following comparison :—

	Synchronous Motor.	Condenser.
	£	£
Capital cost	1,100	720
Annual cost of energy wasted ...	137	34·2

These figures speak for themselves. They would be still more striking if the comparison included necessary spare apparatus, and particularly if any attempt were made to provide a similar total correction, often more effectively, by subdivision into smaller motors placed about the system.

It will be clear that a large condenser could be subdivided without disadvantage, but in the case of synchronous motors such subdivision would involve considerable increase of cost and loss.

No attempt has been made to compare the cost of condensers with the added cost necessary to make ordinary motors or rotary converters available for power factor correction in addition to their ordinary work, but the low capital and working cost of the condensers points to a comparison, even on this basis, being possibly favourable to the latter.

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The author ventures to draw renewed attention to this subject in the hope that something may now be done in the direction of satisfactorily using condensers on alternate-current systems.

In conclusion, it may be of interest to give the result of some experiments on the use of condensers for preventing or stopping the formation of arcs under certain conditions. In investigating the action in a surface-contact tramway system recently, the author found that trouble was experienced due to the formation of persistent arcs at the underground contacts. When the road was wet and dirty a small leakage current passed from the live contact stud under the car over the surface of the road to the rails. When the car had passed and the underground contact-piece had separated its proper distance from the live conductor, this leakage current was sufficient to maintain an arc across the air-space of the contact-maker, thus keeping the stud alive so long as the arc persisted. It was found that with a terminal voltage of about 560 volts the voltage between the stud and the rail was usually about 400 to 440 volts, and the voltage across the arc about 120 to 160 volts. Sometimes arcs would persist for a few seconds with not more than 0·6 ampere, and they would often persist when the leakage current was over 1 ampere—this latter condition, it will be seen, corresponds to a resistance of the leakage path from the stud to the rail of a maximum of 440 ohms.

The prevention of these arcs by increase of gap, or by other structural alterations was not found to be practicable, and it therefore remained to try to find some means for preventing their formation, or for immediately putting them out if they were formed. For this purpose experiments were made with a condenser, which was found to be quite effective.

Two conditions may be given :—

(A) A suitable condenser placed across the gap prevents any arc being formed however small the gap—for example, it was not possible to maintain an arc across a gap of even $\frac{1}{64}$ in.

(B) If the arc is formed and it is then shunted by a suitable condenser it will at once go out.

The minimum safe capacity for these two cases was found to be as follows :—

Amperes.	Condition (A).	Condition (B)
	Microfarads.	Microfarads.
1·5	1	2
2·0	2	4
2·5	3	6
3·0	4	8

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It was found quite practicable to extinguish the arcs by shunting them by a condenser carried on the car, one terminal being connected to the collector or skate, the other to a small wire brush hanging down under the rear platform of the car, and making successive contacts with the studs.

It was also found that the arcs could be put out by placing the condenser in shunt across the leakage path instead of across the arc itself, or with two condensers in series across the resistance and the arc, with a middle connection to the junction between them.

It was not necessary that the condenser should be in a discharged condition, the arc being put out, whether the condenser when applied was discharged or when it was charged to the full voltage of the circuit, in which latter case the effect would be produced in whichever direction of polarity the condenser was applied.

The arcs could also be put out by a resistance shunt but there are objections to that, and in any case it need not be examined here.

The author wishes to express his thanks to Messrs. Isenthal & Co., for the use of some Moscicki condensers, and to Mr. A. E. Levin for substantial assistance in the experiments and in preparation of the paper.

Discussion.

Mr. Mansbridge.

Mr. G. F. Mansbridge: I am sure we are all indebted to the President for showing us a little more than we knew before of what happens inside these condensers. I am very glad to know that the power factor comes out at such an extremely small figure. There are several points I should like to make concerning the paper, but as the time is so short I will cut them down.

It may seem like hypercriticism, but there is one point to which I should like to draw attention. On page 619 Mr. Mordey uses the words "the metal being vaporised" to express what happens in a Mansbridge condenser when a short circuit is created and the fault seals up.

There is no doubt that the metal becomes vaporised if the conditions are favourable, as, for example, when treating the foiled paper in the dry condition before making it up into a condenser. In this case special provision is made for obtaining a large spark at the weak spots as they pass over the "breaking-down" roller, and under such conditions the metal undoubtedly becomes vaporised to some extent, but the automatic sealing effect does not depend so much upon volatilisation of the metal as upon the interesting property possessed by the foiled paper of becoming non-conducting on being strongly heated. This property results from the fact that the tin coating is not an absolutely continuous film, but is a thin layer of metal which has been reconstituted from powder and made coherent by heavy mechanical pressure. Such a film being excessively thin, and having but little natural cohesion, is readily disintegrated by the heating effect of a spark. The point I wish to emphasise is that even with a high voltage a breakdown in a

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condenser of this type does not result in the formation of an arc because of the comparatively small current-carrying capacity of the electrodes. The effect may be likened to an attempt to form an arc between the ends of two extremely fine wires. Obviously in such a case the arc, if formed, must be self-destructive. Mr. Mansbridge.

With regard to the supply of condensers for high-tension work, I think it is purely a question of supply and demand. At the present moment the Helsby Company and other firms are making low-tension condensers by the thousand. They get orders for high-tension condensers by ones and twos, and it is much more convenient from the manufacturing point of view to take low-tension condensers of standard sizes and couple them in series rather than to alter the winding machines, put in a great number of papers and so forth, and make high-tension condensers direct.

That is the only reason—or, at any rate, the chief reason—why low-tension condensers are used for building up high-tension condensers. If it is proposed regularly to run low-tension condensers in series, I would suggest as an alternative that, if possible, the tension be lowered and put on to the condensers in multiple, because there are obvious advantages in not having 10,000, or even 2,000, volts across the terminals of even a pile of condensers if just as good results can be obtained by putting in a transformer and running at the lower pressure. But that is a matter of compromise; I suppose all design is more or less a compromise. With regard to diagram No. 1, I should like to know the temperature at which the tests were taken. Probably it was about 60°, but that is a point I should like to see noted on the diagram. Our President has told us that he has run one of these condensers—I presume this particular condenser—at 400, 500, and 600 volts and 83 periods, for something like three days continuously, and the temperature rise was only 4° or 5° F. That being so, it is evident that the question of the actual temperature of the test is not of great importance, but the insulation and the dielectric strength of condensers, as well as other factors with regard to their behaviour, depend so much upon the temperature that I think it well to raise the point, and also to inquire whether it was the same, or approximately the same, for all the tests.

Referring again to diagram No. 1, I would like, if possible, to have the C^2R loss separated from the dielectric loss. The author refers later on to C^2R losses, but there, I think, he is referring to the C^2R losses due to the actual leakage current through the dielectric. I do not mean that; I mean the C^2R loss in the electrodes, due to their ohmic resistance. The Mansbridge condensers at present on the market are designed for comparatively small currents, and not for continuous work; they are made, in fact, almost entirely for telegraph and telephone purposes, so that the quantity of tin is kept down as low as possible. For these requirements the electrodes have quite sufficient conductivity; but if condensers are required for running continuously at full load a heavier coating of tin might be advantageous, so as to

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Mr. Mansbridge.

bring down the C^2R loss in the electrodes, although this is already very small. If that loss could be separated from the dielectric hysteresis loss the information gained would be useful, because, as I have said, the C^2R loss can be cut down by design. The author has shown that the total loss in this condenser is less than in the glass condenser, but, nevertheless, I am not satisfied that we have brought the loss down to the minimum, either with regard to C^2R or dielectric.

It may be that by reducing the thickness of wax in the condenser the dielectric loss may be reduced, but at present I am not prepared to make a definite statement on that point.

The experiments on the arcs were, I think, particularly interesting. I should like, if I may, without spending too much time, to refer to the rather paradoxical effect produced here as compared with the effect noticeable in a cable relay. S. G. Brown uses a condenser across a breaking contact, or a doubtful contact, to maintain the current and to prevent a break in continuity. Our President uses the condenser across the break to insure the break. In the Brown relay, so far as I recollect, there is a rotating drum and a contact resting very lightly upon it. Difficulty was found in maintaining continuity between the drum and the contact until a condenser was put in shunt across that potential break, and as soon as the condenser was put across continuity was maintained. That seems to be an action exactly in the opposite sense to that which we have seen here across these carbon arcs. It may be suggested that the condenser in the Brown relay acts merely as a shunt path, and that the breaks between the contact and the drum continue precisely as before, but there is reason to think that this is not the case. From this point of view it may be of interest to refer to the effect of adding a condenser to the "breaking-down" device which is used for treating the foiled paper before it is made up into condensers (*vide Journal*, vol. xli., p. 547, 1908). In this treatment the paper is passed in a continuous strip, foil side uppermost, over a metal roller. The roller is connected to one pole of 100 volts, and the other pole is connected to a rubbing contact on the tin side of the paper, so that whenever a defect passes over the roller there is a momentary spark and the defect is eliminated. Now it can readily be shown experimentally that, although there may be plenty of current available for this process, the number of weak spots picked up by the process is doubled or even trebled by putting a condenser of large capacity across the mains. The effect does not seem to be due to the presence of self-induction in the circuit, because an appreciable resistance may be inserted in series with the condenser without disturbing the effect.

Mr. Esson.

Mr. W. B. Esson: We have listened to-night to a very interesting paper. There is no doubt that the condenser would be a decided blessing in many instances for power work, but I believe the reason why it has not made the progress which was expected of it is because it has never until recently been an engineering piece of work. Mr. Mordey will remember, as I do, that when the dynamo first appeared in this country the armature consisted of a ring of iron

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wire wound round with insulated copper wire having a wooden hub for a centre. That was a machine made by instrument makers. It so happened that the dynamo very soon came into the hands of engineers, who made a thorough good job of it, but condensers remained instrument makers' designs, and did not come into the hands of engineers who alone could make them of use for power stations. The Stanley Manufacturing Company of America, I believe, at one time supplied as part of their equipment for 2-phase motors a pair of condensers. It is a very long time since I read of that, and I am not sure what success they had with them, but at any rate, they were fully alive as to the use of condensers. I think the Moscicki condenser is a thorough engineering piece of work. Two years ago I had the pleasure of looking over the factory in Fribourg, where the Moscicki condensers are made, and I was struck with the way in which Mons. Moscicki and his colleagues had taken in hand the old Leyden jar of the laboratories, and had turned it into a thoroughly reliable piece of engineering suitable for use in the power station. At that time I was conducting some experiments at the Fribourg University, and we had these condensers in use on 6,000-volt circuits for the best part of a week, night and day. They behaved all right, and there is no reason why they should not work for years in the same way. With regard to the phase rectifier, which the author calls more sensibly the compensating motor, such machines have been used with great success for the transmission of power to the Kolar goldfields in India. There they were troubled with the lagging current at the start, because they used only induction motors; but later they installed synchronous motors, not only for the purpose of compensation, but to do useful work. They were excited so as to greatly increase the power factor, and thus increase the power-transmitting capacity of the station. That was a case in which compensating motors were actually used as described by Mr. Mordey, but there is no doubt that condensers would be often more convenient, and would also save cost, if they could be made reliable. Mr. Moscicki has certainly done a great deal in the latter direction. Mr. Esson.

Mr. J. E. TAYLOR: There is one point I should like briefly to refer to, and that is the method of the measurement of these losses in condensers. I venture to think there are rather better methods available than by the use of a wattmeter, where such small capacities are concerned as we have in the case of the Moscicki condenser. The thermo-galvanometer appears to lend itself particularly well to the measurement of C^2R losses or dissipation losses of any kind, and it is entirely free from corrections due to either self-induction or capacity of the measuring instrument. By including in the measuring circuit a fine filament of wire of known resistance and of negligible inductance or capacity, even when one reaches very high frequencies, it is possible to determine with accuracy the C^2R losses in the circuit simply by varying the known resistance in the circuit and thereby determining the unknown. The idea is that when a known resistance is put into a circuit of such a value that it gives the maximum power dissipation Mr. Taylor.

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Mr. Taylor.

in that known resistance, then the measured C^2R losses must equal the other dissipation losses in the circuit. Hence by varying the known part the total dissipation can be obtained. It is necessary, however, to so dispose the measuring circuit in relation to the source of alternating current that no reaction on the source is produced. It will, in general, be convenient to utilise mutual induction between the circuit containing the source of alternating current and the measuring circuit, and in such a case the mutual induction (or coupling) should be kept very small. With this precaution the method is capable of very considerable accuracy.

Mr. Swinburne.

Mr. J. SWINBURNE (*communicated*): The President's paper carries one back and makes me feel twenty years younger. Twenty years ago there was a good deal said about them, but there were very few condensers. I, or rather my firm as it then was, made condensers about 1891 to take up the wattless or idle current of hedgehog transformers. These condensers were made of oiled paper. The paper was first dried for some days, then further dried under vacuum, and then treated with paraffin. The paraffin was to keep it dry, not to insulate; it reduced the insulation resistance. We made some specimen condensers that kept their charge for three weeks without perceptible falling off, but the commercial condensers were not so good. We tried mica, waxed paper, glass, and other dielectrics. We found glass heated, and this trouble is present, I believe, in all dielectrics whose inductive capacity is abnormal with reference to its index of refraction. As an alternative of condensers over-excited motors were discussed. The idea was to uncouple one or two generators from their engines and let them run light and over-excited. This was published about 1891, but people have tried to patent it several times since, and I have had excited communications from people who want to oppose the grants.

The uses of leading currents are more numerous than generally supposed. A leading current can be used for exciting a dynamo by armature reaction or increasing its excitation. This was the cause of the phenomenon known as the Ferranti Effect in the Deptford mains. I remember reading a paper before the Physical Society pointing out that the ordinary resonance theory of self-induction and capacity would not explain the phenomenon, and that the armature reaction theory would. Many immediately came forward who assumed that I had never heard of the resonance theory. It was therefore explained to me in an elementary way, and given as the solution of the question, but the self-induction was always merely L, and they never gave it in henries or secohms, and never explained how the enormous self-induction necessary to produce the effect could exist in the circuit. The leading current can also be used to alter the ratio of transformation of a transformer by making the inductive drop act in the opposite direction.

How far it would pay to use condensers to prevent arcing at switches I do not know. Of course, the President's application

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to the surface conduit system is a very special case, and it would have occurred to very few people to try such a solution. Mr. Swinburne.

A new form of electrodynamic condenser was brought before the Institution in 1902.* I have since found out that M. Leblanc is the real inventor either of this or something very like it, and I would like to take this opportunity of calling attention to the point. M. Leblanc's catalogue of inventions is already very large.

Mr. G. L. ADDENBROOKE (*communicated*): I am glad Mr. Mordey has drawn attention to this question, as there is no doubt that a cheap and reliable form of condenser would find many applications in heavy engineering, as has already been the case in telephone and telegraph work, since the mechanical method of making condensers was introduced. Mr. Addenbrooke.

In the first place, as to the power factors of the condensers, I cannot help thinking that Mr. Mordey's results look somewhat low. I tested one of the Mansbridge condensers some time since by the electrostatic method, and got a higher power factor than that given by Mr. Mordey. It is true that I have obtained smaller figures than those given by Mr. Mordey on a Muirhead condenser, which I used as a standard and which is also made of paraffined paper, but this is of course a much more expensive article. Different samples of condensers differ, and it may be that Mr. Mordey has an unusually good sample, or that I was testing nearer the breaking-down point; but I think it would be wise at present to take it that the power factor of these condensers is not much under 1 per cent., the loss Mr. Mordey allows in the example of its use which he gives at the end of his paper. My tests were carried out with an electrostatic wattmeter direct across the circuit, and which only needs in addition a series non-inductive resistance, across which the quadrants are placed, the loss in which is comparable with that in the condenser itself. As no transformers were used or resistances other than the one above mentioned, the chances of introducing error are a good deal less than with the dynamometer method of testing, while the electrostatic wattmeter itself is adapted to give good readings with small currents.

I had not had an opportunity of testing the Moscicki condensers, but was under the impression that the power factor of this type was rather above that given, and I am somewhat surprised that the power factor of the Leyden jars tested by Mr. Mordey came so near that of the Moscicki condensers, as I understood that the silvering direct on the glass reduced the losses considerably as compared with tin foil applied as it is to Leyden jars, and some tests which I made on an ordinary Leyden jar some time since bore out this assumption. Other experiments I have made show that there is a great deal in the way the conductor is applied to the dielectric.

It may appear academic to discuss the question of whether a power factor is $\frac{1}{2}$ of 1 per cent. or 1 per cent., but an example will make it clear how important the difference is from a practical point of view

* *Journal of the Institution of Electrical Engineers*, vol. 32. p. 26, 1902.

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Mr. Addenbrooke.

and how well worth further study. For instance, take the condenser suggested by Mr. Mordey for 10,000 volts and 1 microfarad capacity and occupying a space of about 2 cub. ft. At 10,000 volts this condenser would take a current corresponding to 31 apparent kilowatts, and therefore the loss at 1 per cent. power factor would be 310 watts. Now I think the experience of members will show that 310 watts expended within 2 cub. ft. of material, which is not a good conductor of heat, would lead to an inadmissible rise of temperature, unless considerable subdivision and good ventilation were effected. On the other hand, if the power factor were half this the heat would only be half and would be very much more within practicable limits.

The behaviour of Moscicki condensers on 10,000 volts continuous pressure as compared with the low voltage is very interesting, and engineers certainly owe their thanks to Mr. Mordey for having made the test.

On the application of condensers to practical purposes, provided they they can be sufficiently cheaply manufactured with a requisite margin of safety, I think Mr. Mordey has been unduly modest, as he has not taken credit for the saving capital costs of mains which may be attained as well as the improvement in the working of alternating generators. For instance, take the case Mr. Mordey gives and assume that the 1,000 k.w. are transmitted 5 miles to a sub-station or stations where it is to be transformed statically as often happens. If the full-load current has a power factor of 0·8 the introduction of condensers would bring this up to unity, and the cables themselves would therefore be good for the transmission of 20 per cent. more energy, or 200 k.w. more than in Mr. Mordey's examples. As the cost of laying such a main would be from £8,000 to £10,000 complete, and as the ability to take another 200 k.w. through it might in some cases save the necessity of laying another main, the gain under these circumstances would be very material indeed, and would be in addition to the improvement in the working conditions of the generators.

Mr. Isenthal.

Mr. A. W. ISENTHAL: (*communicated*): Several of the speakers who took part in the discussion considered that in so far as there was not much demand for high-tension condensers they had not been developed on commercial and engineering lines, and were therefore more or less in an experimental stage.

Now, although there certainly has been little demand in connection with heavy engineering work in this country, I should like to point out, that so far as the Moscicki condenser is concerned, this remark does not apply; in the first instance, its application as a most efficient protective device for overhead lines has been considerable, especially in countries like Switzerland, Northern Italy, and South-Eastern France, where extensive power-transmission systems working at extremely high voltages are everywhere met with, and I may say in this connection that there are at the present time some 16,000 condensers thus in permanent use with the most gratifying results.

These condensers are, as it were, constantly under current, being

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joined on the one side to the line and in the case of 3-phase supplies having their outer coatings joined together and earthed. Mr. Isenthal.

The number of failures or breakdowns due to imperfections in manufacture has been somewhat under 6 per 1,000 condensers supplied, which we may consider extremely satisfactory.

Another very large field for these condensers has been created by the development of powerful transmitting stations for long-distance wireless telegraphy, and the same condensers (with perhaps one or two small modifications required by the particular nature of the work) have been used by almost every Government both on the Continent and in our own country on a very large scale indeed.

I mention these points merely to show that there has been a demand for reliable, efficient, and technically acceptable high-tension condensers, and that therefore their evolution has been something tangible, and they may be said, as one of the speakers pointed out, "to be a thorough engineering piece of apparatus."

Reverting once more to their reliability on high voltages, I may say that I have seen condensers running at 60,000 volts for hours, and that, on an oscillatory circuit which is extremely searching for any condenser on account of the extreme peakiness of the curve, and to mention only one installation, there are 165 complete batteries of condensers installed at the various sub-stations of the Entreprise de Thusy-Hauterive system near Fribourg, which are under constant pressure (for days and months) at 32,000 volts effective.

With regard to the comparisons made by the President on the loss in the Moscicki condenser and the Mansbridge condenser, it should not be forgotten that the conditions of experiment were not the same for both types of condensers in so far as the Mansbridge condenser is a low-tension condenser which, according to Mr. Mansbridge's own declaration, was made for telephone and telegraph work particularly, and which even the makers—namely, the British Insulated and Helsby Cable Company—say they have never made up for high tension, and I do not know whether it is perfectly acceptable to extend the results of tests made on an existing piece of apparatus to a possible combination of such apparatus, and it would be interesting to learn what the result would be on the self-sealing properties of the Mansbridge condenser if Mr. Mansbridge's suggestion to thicken the metallic coating was carried out.

Moreover, on Mr. Mordey's own showing, the figures obtained for the Moscicki condenser cannot be taken on the same basis of accuracy as those of the Mansbridge condenser.

It seems rather doubtful to me whether the subdivision—for cooling purposes of a paper condenser as advocated—would be a desirable method.

I take it that the multiplicity of internal connections (say 50 for a 10,000-volt condenser) would certainly introduce possible difficulties and largely increase the space required.

The Moscicki condenser is now made for purposes other than

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Mr. Isenthal.

wireless telegraphy in two types, up to 18,000 volts effective and up to 30,000 volts effective.

I trust that these voltages may be considerably extended in a short while when their manufacture in this country is in full swing.

Mr. Mordey.

Mr. W. M. MORDEY (*in reply*): I am interested to hear from Mr. Mansbridge that he thinks the metal is not vaporised. I spoke from a recollection of his lantern photographs showing greatly magnified images of the faults, and their appearance was consistent with the idea of a small amount of metal deflagrated leaving a clear space round a small hole.

As to the temperature, the tests were made at the ordinary temperature of the test-room, probably about 60° F.

As to the C^2R loss in the conductor of the condenser, I think, perhaps, that may be less important than Mr. Mansbridge supposes. The total loss in this condenser from all causes is only $4\frac{1}{2}$ watts. Certainly a large proportion of that loss is in the dielectric, so that the possible reduction in the total loss by an increase of the cross-section of the conductor must be small. The straightness of the loss curves supports this view.

I do not think I have anything more to say now—except that my object in reading the paper was a very humble one. I merely wished to act as a signpost to a road that it might pay us, as engineers, to explore.

Added later: Mr. Mansbridge suggests transforming down to a lower voltage and putting the condensers in parallel. He rightly says this is a matter of compromise. Has he considered that the losses in the transformers would probably be two or three times as much as in the condensers, and that they would more than double the cost of the installation?

Mr. Taylor refers to testing by a thermo-galvanometer instead of by a wattmeter. I am sorry to say I have no experience of such a method. There is certainly room for improvement over wattmeter methods. Mr. Taylor might usefully give us a paper on the subject with results of experiments.

Mr. Isenthal gives some interesting figures, showing that Moscicki condensers are in use to a greater extent than I supposed.

He objects to the series arrangement of paper condensers—that they would involve many connections. That is true—but with glass condensers there would also be many connections, as the units are small. I agree, however, that parallel connections are better than series connections.

I also agree that there is not yet sufficient information to say definitely to what extent paper condensers can be adapted to high-pressure power purposes. My object was to find out what the losses were, and to draw attention to the whole subject with a view to encouraging the use of condensers of one sort or another for the improvement of the power factor on distribution systems. I think I ought to say that the makers of condensers admitted that they had no information what-

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ever on the subject of the losses; and, indeed, put forward calculations based on the assumption that there were no losses; the only way to find what the losses were was to make tests such as I have described. The use of condensers for phase rectification on power circuits and comparisons with results attainable by other methods could not be properly studied without this information. Mr. Mordey.

I am obliged to the other contributors to the discussion. Their remarks help to elucidate the subject, but do not call for any special reply from me.

The CHAIRMAN (Mr. C. P. Sparks): I will now ask you, gentlemen, to accord to your President a very hearty vote of thanks for his interesting paper. The Chairman.

The resolution of thanks was carried by acclamation.

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SOME CONSIDERATIONS IN THE MANIPULATION OF DRY CORE TELEPHONE CABLES.

By F. G. C. BALDWIN, Associate Member.

(*Abstract of Paper received from the* BIRMINGHAM LOCAL SECTION, *February* 11, *and read at Birmingham, April* 21, 1909.)

The object of this paper is to present, as briefly as possible, some of the more important considerations occurring in actual telephone practice, to describe the various operations which a telephone cable undergoes after its manufacture, and to endeavour to illustrate what is done by the National Telephone Company to secure the greatest working efficiency. A few of the chief appliances and fittings used in connection with these cables will also be described.

The superiority of the dry core, air space, or paper core cable is now universally accepted, and its advantages being well known, they need not be further commented upon.

It is agreed that the "duct" or "conduit" system of installation best facilitates repairs, renewals, inspections, etc., which is not the case with the solid system. The duct system only, therefore, will be considered, and the remarks which follow refer chiefly to the type of metallic circuit cable used for subscribers' lines and short local circuits.

A description of the constructional features of dry core cables is unnecessary, as they are generally known. Table I., which has been extracted from the National Telephone Company's specification for dry core cables with 10-lb. conductors, gives details of the number of pairs in the core and several layers. One or more "marked pairs" are usually provided in each layer.

The methods of laying cables are well known to electrical engineers, and therefore need no detailed description. Owing to the loose way in which the wires of dry core cables are disposed inside the lead sheath, extreme care is essential in handling so that injury to the lead sheath may be avoided.

The various methods adopted in drawing cables into ducts are as follows :—

1. *Directly by Hand.*—Hand hauling is restricted to short lengths of small cables.
2. *By means of Pulley Blocks and Chain or Rope Tackle.*—Used in special cases only.

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3. *By means of a Manually Operated Winch.*—This method is most commonly used, and has proved its superiority for general work.
4. *By means of a Power-driven Winch.*—As far as is known to the author, no power agent has been adopted in this country which is more economical than the manually operated winch.

Opinions differ as to whether a rope or a chain is the best for hauling. The difference in prime cost is negligible. For large and heavy cables a 4½-in. rope is usually used.

The attachment of the cable to the rope or chain is a matter of considerable importance. For this purpose a wire "grip" has been

TABLE I.

Dry Core Telephone Cables.

(With 10-lb. Conductors.)

Number of Conductors.	Number of Pairs in the Several Layers.												
	Centre.	1st.	2nd.	3rd.	4th.	5th.	6th.	7th.	8th.	9th.	10th.	11th.	12th.	13th.
Pairs.														
5	1	4	—	—	—	—	—	—	—	—	—	—	—	—
8	1	7	—	—	—	—	—	—	—	—	—	—	—	—
10	2	8	—	—	—	—	—	—	—	—	—	—	—	—
15	5	10	—	—	—	—	—	—	—	—	—	—	—	—
20	2	6	12	—	—	—	—	—	—	—	—	—	—	—
25	3	9	13	—	—	—	—	—	—	—	—	—	—	—
50	4	10	16	20	—	—	—	—	—	—	—	—	—	—
75	4	10	15	20	26	—	—	—	—	—	—	—	—	—
100	3	9	13	19	25	31	—	—	—	—	—	—	—	—
150	4	10	16	21	27	33	39	—	—	—	—	—	—	—
200	4	10	16	22	28	34	40	46	—	—	—	—	—	—
250	4	10	16	21	27	34	40	46	52	—	—	—	—	—
300	3	9	14	20	26	32	38	46	52	60	—	—	—	—
400	1	6	12	18	24	30	36	42	48	55	61	67	—	—
500	2	8	14	20	26	32	38	45	51	57	63	69	75	—
600	4	10	16	22	28	34	40	46	52	58	64	70	75	81

Any extra pairs to be put in the outer layer.

universally adopted, which avoids mutilation and consequent scrapping of the cable end. The grip consists of a woven cylinder of steel wire, interlaced in such a manner that contraction ensues upon the application of tension. In use it is simply slipped over the end of the cable, and tightens up when hauling is commenced. Some preliminary preparation of the end of the cable is necessary, and in some cases where heavy lengths are being dealt with it is advisable to open the end of the cable, and, laying bare the conductors for a few inches, to plumb them solid with the lead sheath. This ensures the tension being equally distributed amongst the conductors, and avoids the possibility of the lead sheath parting. A lubricant in the form of petroleum jelly is usually applied to the cable as it enters the duct. The speed of travel of cables varies from about 3 to 8 ft. per minute. By judicious arrangement it is in many cases possible to deal with cables of small

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diameter (not exceeding 1¼ in.) without cutting or jointing in the maximum lengths in which they can conveniently be manufactured. The cable is first drawn in from a point intermediate between the two extremities of the section—where a break in the conduit line exists—to one end of the section in the ordinary way, after which the remainder is flaked off the drum and laid upon the ground in the form of a figure 8. The free end is then attached to the rope, and hauling proceeds in the opposite direction until the whole has been laid. Lengths of nearly 800 yards have been successfully dealt with in this way and the cost of a joint saved.

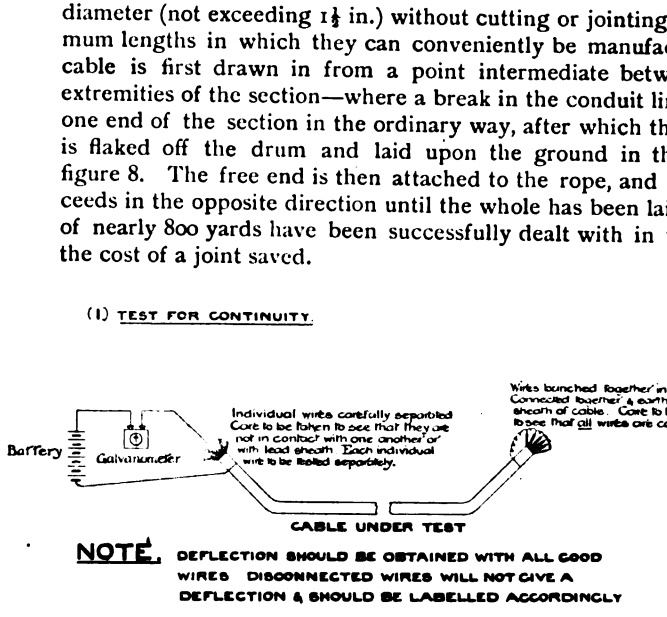
(1) TEST FOR CONTINUITY.
Battery
Galvanometer
Individual wires carefully separated. Care to be taken to see that they are not in contact with one another or with lead sheath. Each individual wire to be tested separately.
Wires bunched together in groups. Connected together & earthed on sheath of cable. Care to be taken to see that all wires are connected.
CABLE UNDER TEST
NOTE. DEFLECTION SHOULD BE OBTAINED WITH ALL GOOD WIRES. DISCONNECTED WIRES WILL NOT GIVE A DEFLECTION & SHOULD BE LABELLED ACCORDINGLY
(2) TESTING FOR EARTH, CONTACT, SHORT CIRCUIT.
Individual wires carefully separated. Care to be taken to see that they are not in contact with one another or with lead sheath.
Wires bunched together in groups. Connected together and earthed on sheath of cable. Care to be taken to see that all wires are connected. Each individual wire to be tested with those untested earthed on sheath.
Galvanometer
Battery
Only one wire connected at a time
CABLE UNDER TEST
NOTE. No deflection should be obtained with all good wires. Faulty wire will be denoted by a deflection, and should be labelled accordingly.

FIG. 1.—Preliminary Test (Diagram).

During jointing and its attendant operations precautions are taken to secure the following :—

1. Minimum number of faulty circuits in the completed cable.
2. Immunity from crossed pairs.
3. Lead sheath perfectly air and water proof.
4. Electrical properties up to the standard.

Preliminary Test.—Each length of cable after being laid is subjected to a preliminary test as a primary indication of the existence of faulty wires, which, if found to occur in more than one length, should

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be jointed together. The number of faulty circuits in the completed cable should then be a minimum. The test is reliably made in the manner indicated by the diagram (Fig. 1), which is self-explanatory.

1. Test for continuity.
2. Test for earth, contact and short circuit.

After the test has been carried out all faults should be verified and faulty wires labelled.

Jointing.—In jointing especially is it necessary to observe cleanliness and to exclude moisture. In large joints where the core is exposed for a period of twenty hours or more the moisture absorbed by the dielectric from an atmosphere of varying humidity may be con-

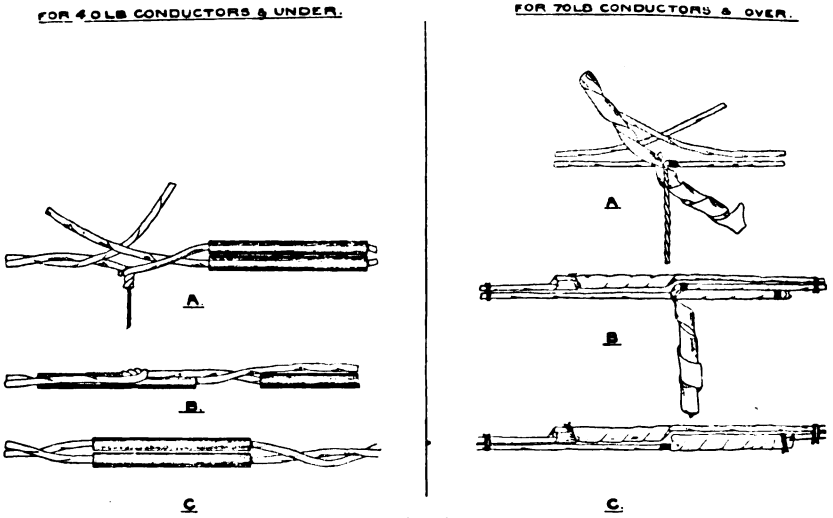

FIG. 2.—Details of Jointing.

(*a*) For 40-lb. conductors and under.
(*b*) For 70-lb. conductors and over.

siderable unless proper precautions are taken. While jointing is progressing heat is applied either constantly or at frequent intervals to expel moisture. After the lead has been stripped off for the requisite distance jointing is performed as indicated in Fig. 2.

(*a*) For conductors under 70 lbs. per mile the wires are tightly twisted together as shown, and insulated by a dry paper sleeve.

(*b*) Conductors of 70 lbs. per mile and over are similarly twisted, but are insulated by their paper covering, reserved for the purpose, and secured as illustrated by a binding of cotton thread.

In both cases the paper is included in the first two twists to prevent it running back, and the joint is not soldered.

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Wires of respective colours should be jointed together. The sleeved or paper-insulated joints should be distributed to secure uniform diameter of completed joint, and the wires should be only moderately taut. After a thorough drying the joint is served with a binding of dry cotton tape without overlap, and immediately afterwards the plumbing is executed, 6 lb. sheet lead, or preferably an unseamed

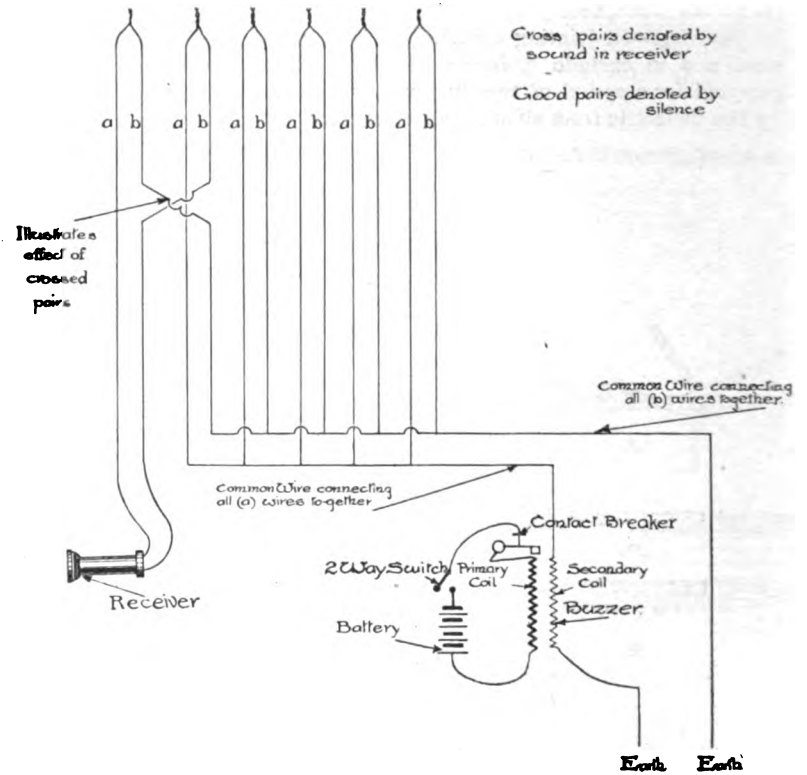

FIG. 3.—Test for Crossed Pairs (Diagram).

sleeve, being used. A brass nozzle with screwed cap and leather washer is permanently plumbed into the sleeve, and by connection thereto of a flexible tube air, dried by passage through a small portable desiccator, is forced into the joint by means of a hand pump. A defect in the plumbing is shown by the continued appearance of air bubbles on the application of soapy water.

The introduction of crosses is guarded against by proving each pair as jointed. Before commencing the first joint the extreme end of the first length of cable is opened, the individual pairs are very carefully selected, and the (*a*) and (*b*) wires of each are connected together and

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insulated. The continuity of each pair is proved at every joint during the proceess of jointing—the joints being made consecutively—by means of a battery and galvanometer. Assuming that the pairs have been properly selected at the end of the cable, this has the effect of—

(*a*) Precluding pairs from being jointed crossed ;
(*b*) Indicating a cross which may have been carelessly interposed at the joint last made.

On completion of the jointing a rough test of the section is desirable as a means of detection of faulty wires. The test may be made in a manner similar to the preliminary test previously described.

Labelling.—It is customary to assign a number to each pair of a completed cable for purposes of distinction. The method of testing out is well known, and explanation is unnecessary.

Test for Crossed Pairs.—Every completed section is subjected to a test for crossed pairs which may have escaped notice during the loop tests made at each joint. The test is diagrammatically illustrated in Fig. 3, and consists in sending round the whole of the pairs connected in parallel an alternating current, each pair being taken one at a time and connected to a telephone receiver. In the diagram it is assumed that a cross exists, and if the circuit be traced it will be apparent that when the receiver is connected to a pair that is crossed with another one a hum will be heard on placing it to the ear. Any such pairs which may be found are labelled accordingly. When the whole of the faulty wires have been detected, it is decided whether the faults are to be located and cleared at once or left for attention as suitable opportunity occurs.

Terminating Dry Core Cables.—The effectual termination of dry core cables is a matter presenting some difficulty. Provision has to be made for termination in positions fully exposed to all climatic influences as well as in protected places, but in all cases there exists the possibility of penetration of moisture to the cable core. Three typical methods of termination in present use are mentioned below :—

1. *Cable Heads or Terminals.*—In these the end of the cable is hermetically sealed within a metal or other chamber, connection being made to the external circuit by means of suitable insulated terminals. Details of a terminal of this type, designed by Mr. S. P. Grace, of Pittsburgh, and made by the Western Electric Company for external use, are given in Fig. 4. It consists of a cast-iron chamber with suitable lugs for attachment to its support and a cast-iron lid hinged at the top. In a recess in the box there is fitted a porcelain block, through which brass pins extend, provided in the inside with soldering tabs and on the outside with screwed nuts and washers. The cable enters through a brass nozzle to which its sheath is plumbed, and the wires are soldered to their respective tabs. The rear compartment is subsequently filled with molten insulating compound through a hole at

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the top, which is afterwards sealed by a screwed plug. Connection to the external circuit is made by rubber insulated leaders as shown.

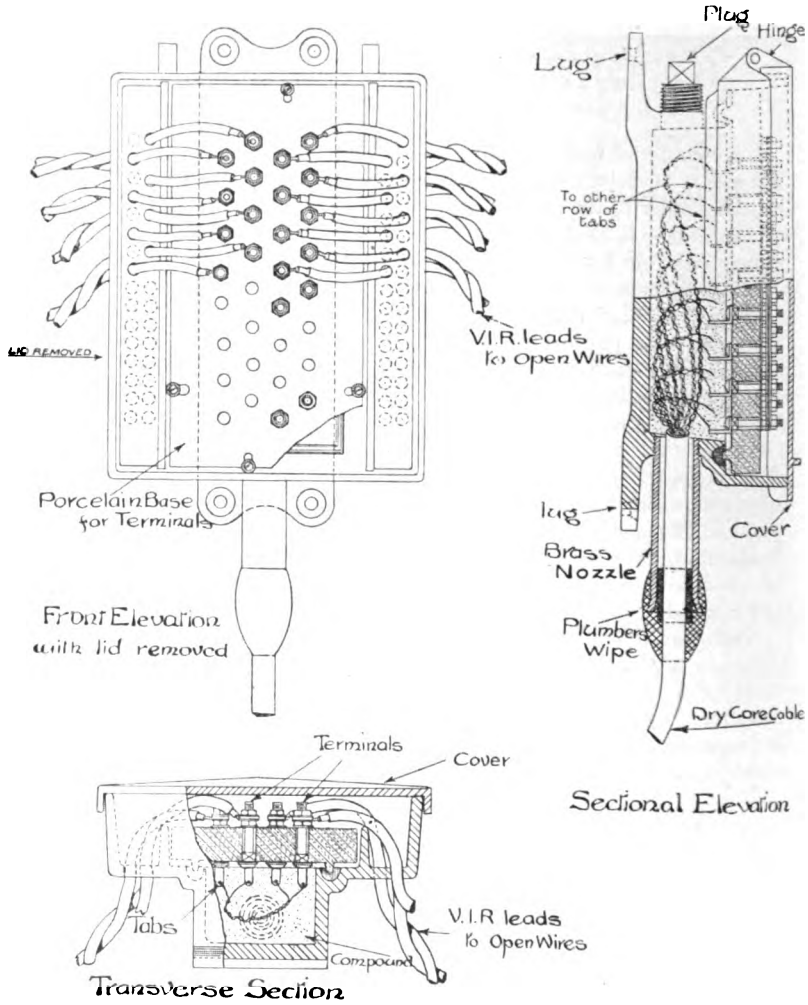

FIG. 4.—Cable Terminal—W.E. Type 14 (Drawing).

2. *Potheads.*—The cable is sealed by jointing its wires to vulcanised indiarubber leaders enclosed in a lead sleeve—to which the cable sheath is ultimately plumbed—impregnated with a molten compound, which, when set, forms an air-tight plug. Potheads are usually manufactured locally as follows: The

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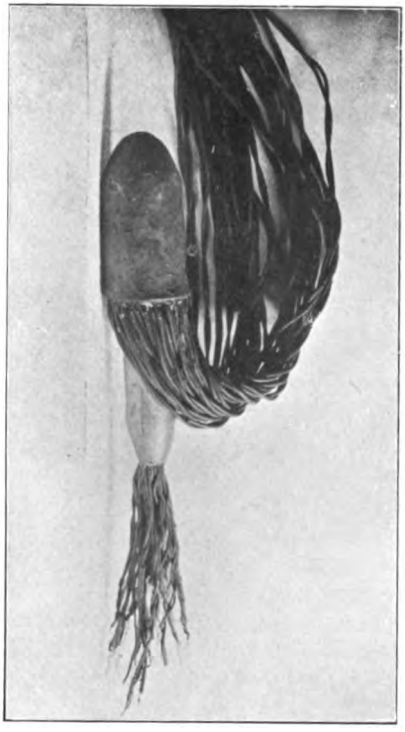

FIG. 5.—Pothead.

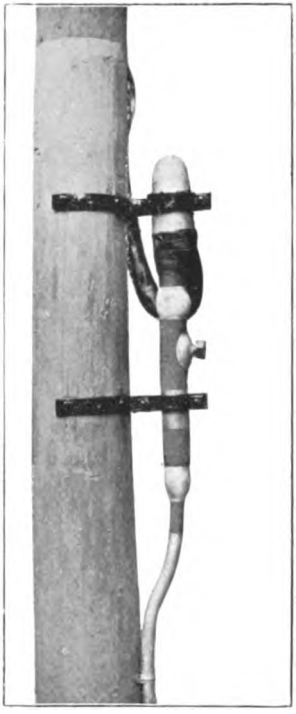

FIG. 6.—Pothead Mounted on Pole.

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requisite number of V.I.R. leaders are cut to the proper length, and at one end of each the outer tape and braiding is very carefully removed for a distance depending upon the size of the pothead being made. It is essential that the dielectric should be stripped clean and be free from injury. The leaders are then tightly and neatly bunched, the stripped portions being laid evenly together, and a lead sleeve of the proper diameter and length is slipped over them and secured at such a point that it encloses the stripped portions, sufficient only being left protruding for jointing to the dry core cable. At this end the lead sleeve is beaten on to the stripped leaders which are protected from injury by a binding of insulating tape. Insulating compound at a temperature of from 250° to 280° F. is then run into the sleeve in such a manner as to ensure it being well filled and the leaders being thoroughly enveloped. When cold, an air-pressure test is applied, the mouth of the sleeve and the leaders being immersed in water so that a leak may be indicated. If sound, the pothead may be used as it is for sheltered situations, but for exposed positions it should be fitted with a lead cap of suitable dimensions. The inverted cap is partly filled with melted compound, and after the leaders have been doubled back and uniformly arranged along the pothead sleeve containing them, the same is inserted and forced well into the cap, superfluous compound being expelled. When cold the pothead is complete and may be jointed to the dry core cable in the usual manner. Fig. 5 is from a photograph of a completed pothead, and Fig. 6 is an illustration of a pothead mounted on a pole.

3. *Terminating by means of Silk and Cotton Lead-covered Cable.*—For inside positions the present practice in terminating a cable of over 50 pairs is to joint it to a special length of silk and cotton insulated lead-covered cable, the intervening joint being filled solid with paraffin wax as a means of isolating the paper core from the atmosphere. The end of the silk and cotton cable, which is to be connected to the terminal apparatus and will be permanently exposed, is stripped of its sheath for the necessary distance, and the exposed core is immediately well saturated with beeswax. The beeswax should be maintained at a temperature of not less than 200° F., preferably by means of a water-jacketed waxing tank, and the cable should not be withdrawn from the wax until the cessation of bubbling shows that all moisture has been expelled. The wax is allowed to penetrate under the lead sheathing as far as possible so that air is excluded from the cable core. Afterwards the waxed wires are formed out in a manner consistent with the disposition of the terminals to which they are ultimately to be connected.

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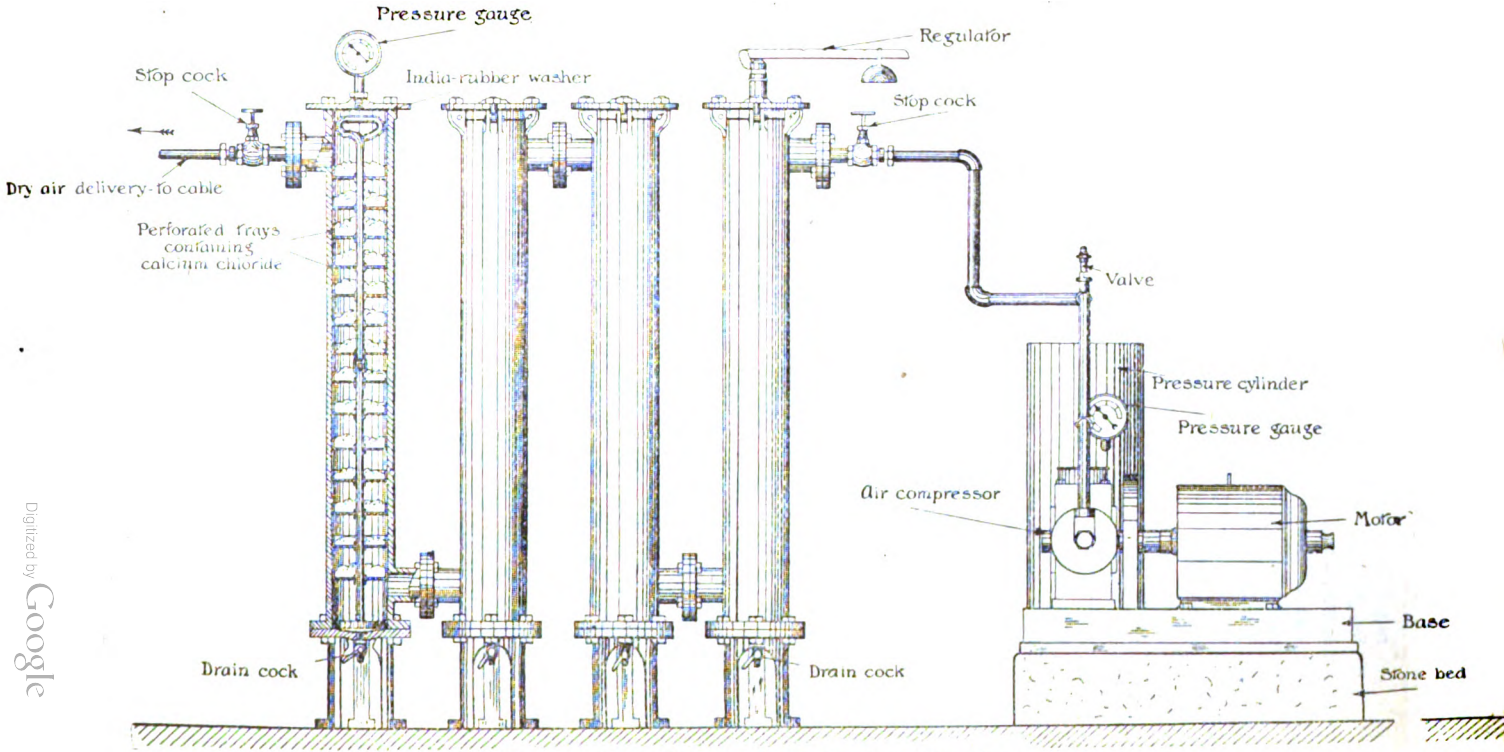

FIG. 7.—Desiccating Apparatus (Sectional Drawing).

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The joint between silk and cotton and dry core cables is made in the usual manner except that the wires are left a little looser and that the ends of the joint are packed with dry cotton-wool interposed between the layers. The taping is omitted, and after being thoroughly dried the joint is plumbed. If the respective tests for insulation and plumbing are satisfactory the joint is immediately filled solid with pure paraffin wax. When cold another insulation test and an air-pressure test are applied.

Air-pressure Test.—To prove that the sheath of all jointed cables is sound an air-pressure test is desirable. Air which has been chemically dried is applied under pressure to one end of the cable until a pressure of about 12 lbs. per square inch is registered by special pressure gauges fitted at its extremities. The air supply is then shut off, both gauges being left connected. If the pressure is maintained without appreciable drop for, say, 10 hours, it may be taken as proof that the cable sheath is air-tight and the cable may with safety be brought into use.

Tests for Insulation, Conductivity, and Capacity.—It is not intended to describe these tests, as the methods adopted and apparatus used are well known. The capacity test is usually dispensed with. The conductivity test serves as a check as to length, and proves the resistance of the twisted joints. The insulation test is of greater importance as the insulation resistance is liable to considerable variation. 500 megohms per mile of circuit may be taken as an average standard, and when the dielectric consists of dry paper core only it should be much in excess of this. Potheads, cable heads, and silk and cotton cables with filled joints detrimentally affect the insulation.

Desiccation.—An improvement in the insulation of air-space cables is readily accomplished. Atmospheric air, from which all moisture has been extracted by being passed through tubes containing calcium chloride, is forced at a pressure of from 15 to 20 lbs. per square inch through the cable of low insulation. The moisture is absorbed by the dry air and expelled along with it at a vent opened in the cable at a suitable point. Fig. 7 represents a desiccating apparatus which is being fitted by the National Telephone Company at its important exchanges. A motor-driven air compressor supplies air at regulated pressure to a chamber which is connected to four vertical cast-iron cylinders. The cylinders are connected in series, and the chloride of calcium is distributed within them on perforated brass trays supported at equal intervals by a central rod. Each cylinder is provided at the top with a flanged lid secured by bolts and made air-tight by a rubber washer, and at the bottom with a blow-off cock for drawing off the extracted moisture. The first and last cylinders are fitted respectively with a lever valve for regulating and a gauge for indicating the pressure.

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Discussion.

Mr. Stuart. Mr. Dudley Stuart: I would point out the great increase in the number of wires now contained in a cable of suitable size to be drawn into a 3-in. duct. A few years ago a 100-pr. cable was the largest size available, but it is now possible to draw a 600-pr. cable into a duct of this diameter. One reason for this advance is that the National Telephone Company have been able to introduce a cable with 10 lb. per mile conductors, and by this means they obtain the 600-pr. cable, which from a mean diameter of 2·55 in. has been gradually cut down to 2·34 in.; I assume every one will appreciate the advantages in the matter of price per duct circuit.

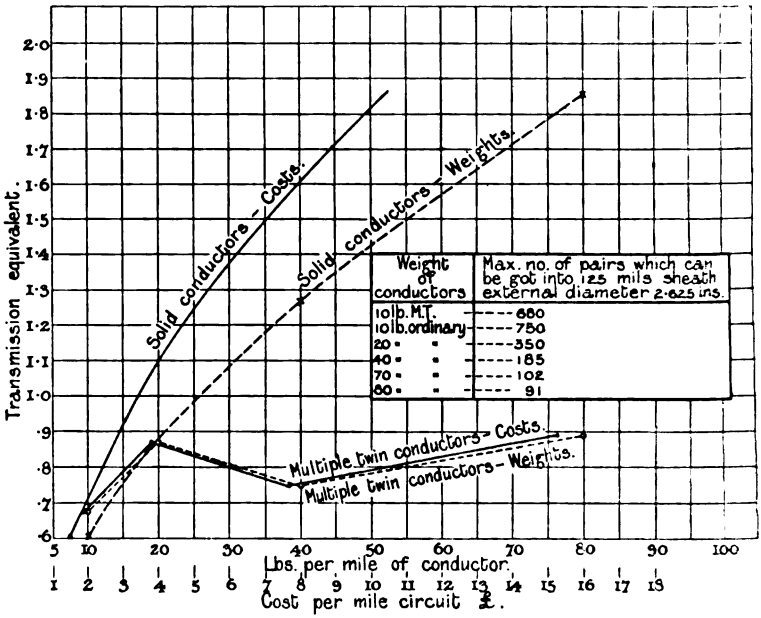

Fig. A.

The policy adopted by the National Telephone Company in the purchase of these cables is to give the manufacturers as free a hand as possible—electrical conditions always excepted—and to avoid tying them too closely to a specification. The result of this policy is to encourage enterprise on the manufacturer's part in making any improvements in the cables, such as a reduction of diameter. I think that engineers generally, both on the power and on the telephone side, are apt to bind suppliers down too much to the specification, with the result that manufacturers have been handicapped by not always being able to introduce improvements which, with their experience, might have been valuable.

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Mr. Stuart.

The National Telephone Company have made a special study of the question of correct sheathing for dry core lead or alloy-covered cable, as there appeared to be some difference of opinion between various authorities, although the Company had always made alloy sheath their standard practice. In Table I. I give a summary of the results of investigations of lead as against an alloy of lead and 3 per cent. of tin, and the deduction which I make is that the alloy offers the greater advantages.

TABLE I.

Comparison of Pure Lead and 3 per Cent. Tin Lead Alloy.

Property.	Summary of Results of Investigation.	More suitable Material.
Tensile strength	Breaking stress, 3 per cent. tin alloy, 3,980 lbs. per square inch ... ... Pure lead, 2,620	Alloy.
Hardness ...	Ratio $\frac{\text{alloy}}{\text{pure lead}} = 1{\cdot}2$	Alloy.
Pliability ...	Ratio of number of alternate strains to produce permanent deformation— $\frac{\text{lead}}{\text{alloy}} = \frac{394}{298} = 1{\cdot}32$ ...	Lead.
Ability to resist corrosion ...	Evidence not sufficient to decide either way	
Facility of bending	For a sheath of given thickness	Lead.
Cost	For a sheath of given thickness For a sheath of given tensile strength	Lead. Alloy.

In pliability it can be seen that lead has the advantage, but as the number of alternate strains to produce permanent deformity is far in excess of that likely to be experienced in practice, pliability is neglected. For facility of bending, also, lead is superior, but this superiority can also be neglected, as it is obvious that for a given tensile strength the resistance to straightening must be the same for whatever material may be employed. This leaves tensile strength as the only factor worth considering, and as for a given tensile strength alloy is the cheaper, the National Telephone Company's practice can be readily understood.

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Mr. Stuart. If, however, the price of tin were to become abnormally high, of course it would be necessary to reconsider the question.

As to conductors of 70 lbs. and upwards, those are provided on long circuits for transmission purposes. A cable has been designed (not by the National Telephone Company) made up of conductors of equal weight, for which it is claimed that by combining a number of circuits the transmission equivalent of heavier conductors can be obtained; but tests do not support the claims made. In Fig. A I give a curve illustrating the shortcomings of the cable made up on this system, both as regards transmission and cost.

Mr. Baldwin. Mr. BALDWIN (*in reply*): I have to thank Mr. Stuart for kindly supplementing my paper with such valuable information. I would point out, however, that I mainly intended to put forward the methods adopted in performing various operations as carried out by the National Telephone Company, in which the best results are secured. As it is a practical paper, I have purposely omitted everything on the design and construction side. Of course a great deal of importance is attached to the design of these cables, but if the operations to which I have alluded are not carried out in practice in a proper and careful manner, I am afraid that much of the labour spent in design will be wasted. Mr. Stuart referred to the relative qualities of pure lead and lead-tin alloy for cable sheaths. I agree that a greater mechanical strength is obtained from an alloy sheath containing about 3 per cent. tin, and that the alloy sheath possesses advantages over the pure lead. Tensile strength is an essential quality as in hauling in cables an appreciable strain is imposed on the lead. It would be a serious matter if it parted, and the location of the break might present considerable difficulty.

As regards the Martin Dieselhorst cable which Mr. Stuart mentioned, in reading my paper I omitted to say that the conductors of heavier section than 40 lbs. referred to are provided in cases where lines of higher transmission value are required.

This is the practice adopted by the National Telephone Company, and the curves given by Mr. Stuart very clearly show the merits of this system.

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ELECTRICITY WORKS AND REFUSE DESTRUCTORS.

By J. A. ROBERTSON, Member.

(*Paper received from the* GLASGOW LOCAL SECTION, *February* 8, *read at Glasgow on April* 13, *and at Dublin on May* 13, 1909.)

The utilisation of heat from refuse destructor furnaces to generate electricity has received much attention both in Europe and America during the past decade. Although the first combination of a destructor with a municipal electric supply undertaking took place at Shoreditch so recently as 1897, there are now no less than 73 such undertakings in this country in operation, and these are being added to at the rate of about 20 per annum. It may be taken for granted that in most cases these installations have proved successful, but there have also been some notable failures, and the value or otherwise of the combination still forms a subject of controversy amongst station engineers, including those who are in charge of combined works.

The author was called on about three years ago to investigate the subject on behalf of his Committee, and more recently to design and supervise the equipment of a combined installation at Greenock, which has been in operation during the past year. He trusts that the results of his experience, which are embodied in the following paper, may prove of some interest to other central station engineers, and may also help to remove some of the misconception which still exists on the subject.

It may be laid down as an axiom that the disposal of towns' refuse by cremation is primarily a sanitary measure. The increasing difficulty of finding a suitable tipping-ground, reasonably near the area of collection, and yet free from possible objection on the score of nuisance, has made the destructor a necessity in nearly all large inland towns. The possibility of reducing the cost of disposal by the sale of scrap iron and furnace clinker, or by the utilisation of what would otherwise be waste heat for steam-raising purposes, naturally appeals to those responsible for municipal administration, and in some instances it would appear as if the commercial aspect of the question has received undue prominence. In some quite modern installations one may see large heaps of refuse stewing on the top of hot furnaces and being turned over and sorted by hand to recover old bottles and scrap iron. The author submits that by dealing in this manner with such obviously objectionable material, local authorities are introducing those very

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conditions which the destructor is designed to prevent, and it cannot be too strongly insisted upon that all question of profit in operating the destructor should be subservient to the requirements of cleanliness and public health.

It is proposed to show in this paper that appreciable benefit can be obtained from the combination of electricity works and refuse destructors under certain conditions. The first is that there should be a fairly steady demand for energy on the electricity works.

The refuse must, of course, be collected daily, and it is desirable for sanitary reasons to transfer it from the collecting carts to the furnaces as quickly as circumstances permit. But unless the steam from the destructor can be utilised during the greater portion of the 24 hours, it will be necessary either to provide sufficient furnace capacity to burn a day's collection in a comparatively short period of time, storing the material as it is delivered, or to bye-pass the hot gases from the furnaces direct to the chimney. Apart from the objection which may be taken to the storage of refuse on the destructor premises, the standing charges on the additional capital will form a serious item in the total costs of the undertaking, while the bye-passing of the furnace gases at a temperature varying from 1,200° to 2,000° Fahr. is not desirable, and will lead to rapid deterioration of flues and chimney brickwork. For these reasons, therefore, and for the further reason that in order to justify the combination in most cases, the whole, or nearly the whole, of the available heat must be utilised, it follows that a continuous load must be available at the power station. In residential districts where current is used chiefly for lighting purposes, it is questionable if any benefit is obtained from linking up the two undertakings, and in many cases it will be found that the disappointing results obtained are due to an imperfect consideration of this condition. Each case requires to be carefully studied on its merits, with due regard to local conditions such as the price of fuel, the quality of refuse, and especially the nature of the demand on the power station. Generally speaking, it may be said that in those industrial districts where a power load exists, or where a tramway supply forms part of the output of the station, the refuse destructor and electricity works can be combined and operated with financial benefit to the community.

The application of thermal storage systems and the employment of storage batteries have been suggested as remedies to level up the load on the destructor boilers at times when there is little or no demand for electricity. Thermal storage was employed in the Shoreditch installation, but does not appear to have made any further headway since, while the heavy capital cost and high maintenance charges of storage batteries would in most cases neutralise any advantage to be obtained from utilising the destructor steam.

The refuse itself may be looked on as a low-grade fuel, which can be obtained free of cost, but requiring the employment of special plant for its combustion. It is found that the material varies in quality according to the district in which it is collected and in the different

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seasons of the year. No definite rule seems to apply, but taking the average of a number of towns in this country I have ascertained that from 15 cwts. to 1 ton of refuse is collected per 1,000 inhabitants per day. The calorific value also varies in different parts of the country and in different districts of the same town. In coal-mining districts, the refuse is naturally better in quality than where coal is dear. It is also the case that the material richest in carbon comes from ashpits in the working-class districts, and it would appear as if the inefficiency of the ordinary domestic fire-grate was responsible for the remarkable steam-raising results obtained in many industrial towns. The worst quality is tradesmen's shop refuse or garden sweepings from residential districts. The chart (Fig. 1) shows the variation in delivery at Greenock during different periods of the year, and as the quantity of ash-pit refuse is less in summer, it will be seen that the value of the whole delivery is correspondingly reduced, so that while it is possible to obtain results as high as 86 units per ton in October, the figure in July falls as low as 24 units per ton. It has been suggested that in certain cases it would be profitable to reinforce the refuse with low-grade coal or coke dust in order to secure uniform steaming, and if a simple process of this kind could be devised which would enable the destructor boilers to be worked at or near their full capacity, irrespective of variations in the quality of the refuse, the steam-raising results could be enormously improved. There are difficulties, however, in designing a furnace to burn refuse and coal at the same time, and as matters stand the great difference in the quality of the refuse delivered from hour to hour and throughout the year constitutes the most serious drawback in combined installations, entailing the use of standby coal-fired boilers to ensure steady steam pressure at the engines.

The principal objection to combined installations by station engineers is the presence of dust or fine grit which finds its way into the engine-room with bad results to the generating plant. The dust arises partly from the tipping of refuse—especially in dry weather—and in the operation of clinkering the fires, but is mostly due to the crushing and screening of clinker. It is only fair to point out that in most cases the dust objection might have been avoided, or at least obviated, by a better arrangement of buildings, and the author can affirm that in the Greenock installation no real trouble has been experienced from this cause.

In selecting a site for a combined works the question of nuisance should not, however, be overlooked, and while destructors may be found in daily operation in the very centres of some large towns, it is desirable, if possible, to prevent any cause for objection. The storage of green refuse, containing vegetable or animal matter, is likely to give trouble, but the nuisance mostly feared—*i.e.*, the emission of dust or offensive gases from the chimney—should not be possible in a modern plant, and is in all cases due either to improper design or to neglect in cleaning out flues and combustion chambers. As a matter of fact, the emissions from the chimney of a modern destructor are nearly trans-

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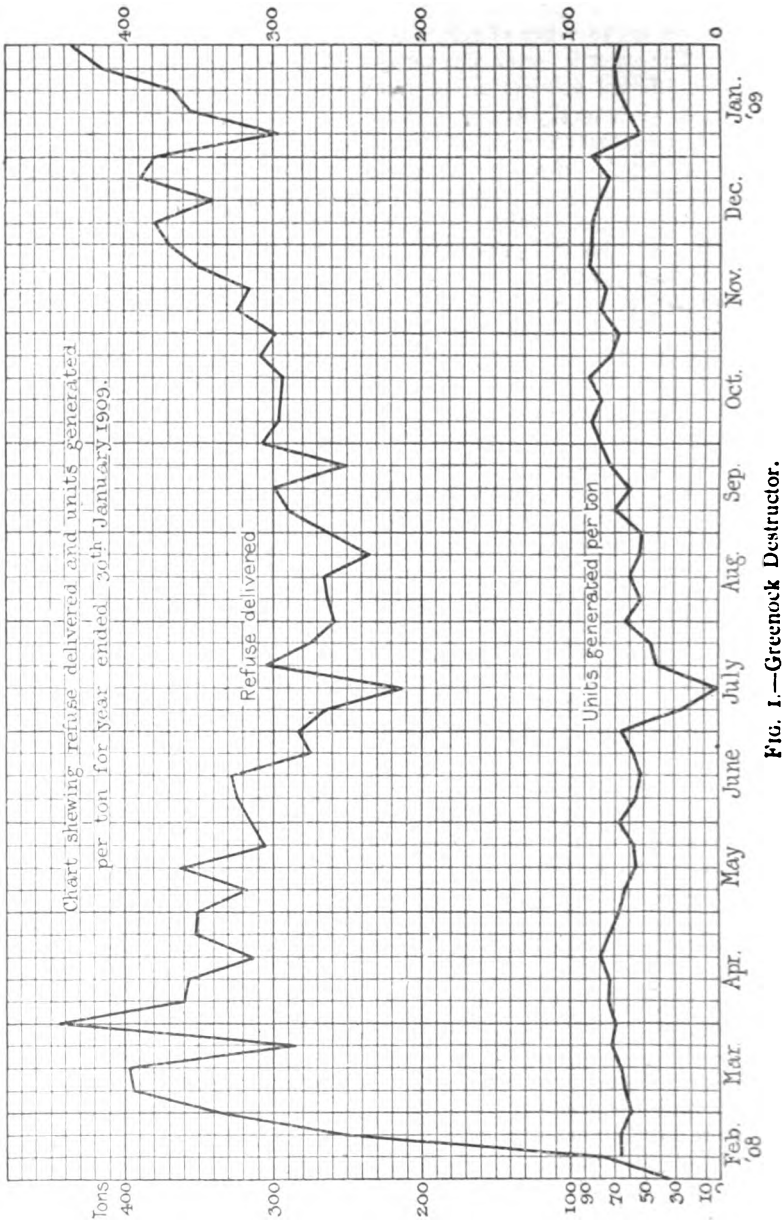

FIG. 1.—Greenock Destructor.

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parent in colour, and less objectionable than the gases liberated from hand-fed coal-fired boilers.

Design of Destructor Plant.—It is not proposed to deal with the evolution of destructor design, nor to describe in detail the different types of plant now in use. These subjects have been dealt with elsewhere, and the following remarks will therefore be confined to some of the more important points in designing a modern installation, with special reference to the works under the author's supervision at Greenock.

The problem to be solved is the destruction by fire under sanitary conditions of material which contains only a small percentage of combustible matter, and which is constantly varying in quality, in such a manner as to utilise to the fullest extent the heat obtainable from combustion in the production of steam. The points which call for special attention are the charging or feeding of the refuse into the furnaces, the system of forced draught employed, the design of furnace and combustion chamber, and the position and type of boiler.

Charging.—The general practice hitherto has been to feed the refuse into the furnaces by manual labour. There are three systems of hand feeding which may be classified as follows:—

(*a*) *Front Shovel Feed.*—Charging and clinkering are performed by hand labour through a door in *front* of the furnaces.

(*b*) *Back Shovel Feed.*—The refuse is fed by hand labour into the *back* of the furnace at the opposite end from the clinkering door.

(*c*) *Top Feed.*—The refuse is tipped from an elevated cartway on top of the furnace. It is then drawn or pushed through an opening in the furnace roof and falls on a drying hearth, where it is manipulated from the clinkering door. In some cases a large storage bin has been erected above, but separated from the furnace, to obviate the objectionable practice of storing green refuse on a hot furnace top.

The drawbacks to all hand-fed systems are the reduction in temperature consequent on the inrush of cold air when charging, and the amount of manual labour necessary for shovelling such difficult material —a process which is arduous and not clean. Simplicity is considered the chief recommendation of hand-fed systems, and it is claimed that by selecting and feeding the refuse better steaming results can be obtained than with other systems.

Mechanical Charging.—The earliest and best known is Boulnois and Brodie's system in which movable iron trucks are employed. The movement of a charging truck opens and closes the furnace door, so that the whole operation of depositing the refuse from the carts into the furnaces is carried out without the intervention of manual labour.

The system adopted in the Greenock installation is the automatic "tub-feed" system, which found favour chiefly on account of its sanitary advantages. In this system the refuse is tipped from the

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collecting carts into tubs or skips, each skip containing one load. The skips are then lifted by an electric crane and deposited on a storage platform, where they are kept till required for charging. This platform is erected over the clinkering floor, and is separated from the furnace brickwork to ensure cool storage. To charge a furnace, the skip is lifted from the platform by the crane and is placed on a movable cradle directly over the furnace opening, which is fitted with a water-sealed door. When released by the crane, the weight of the skip operates a system of levers and a balance weight in such a way as to lift the water-sealed door off the furnace and draw it to one side, so permitting the cradle to descend to the mouth of the charging door. The bottom of the skip consists of two hinged doors suspended so that when the skip reaches the proper position, the doors open outwards, and the contents of the skip are deposited directly into the furnace. The crane then lifts the empty skip, and the water-sealed door, actuated by the balance weight, is drawn back to its seat, the whole operation of opening the door, charging, and reclosing the door having occupied less than a minute.

The principal advantage of the system is, of course, its comparative cleanliness, and as the process of lifting the skips and charging the furnaces of an installation capable of cremating 100 tons in 18 hours can be performed entirely by one craneman per shift, the saving in labour cost as compared with hand feeding is an important consideration. With this method of charging, the reduction of temperature which takes place during the slower operation of hand firing is largely overcome, and the efficiency and capacity of the furnace is correspondingly increased. The disadvantage of the system is that it prevents any selection or proportioning of the charges, while the deposition of a whole cart-load of green refuse into the furnace at one charge is apt to cause fluctuations of temperature with consequent variation in steam pressure.

Furnaces and Boilers.—In modern destructor plants the following are essential features :—

1. Furnace chambers or cells designed so as to embody the principle of mutual assistance in operation.
2. A combustion chamber of sufficient capacity to maintain a high temperature under all conditions of working and designed to act as an efficient dust trap.
3. A system of forced draught.
4. One or more boilers situated between the combustion chamber and the chimney.

Nearly all plants now in operation can be separated into two groups —*i.e.*, those in which the furnace chambers or cells—as they are termed —are isolated from each other, the hot gases from two or more cells being led into a common combustion chamber, and those in which a number of grates—usually three or four—are grouped in a common furnace, separate firing doors and ash-pits being provided for each grate. In

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the isolated system the cells are generally arranged in pairs, each pair with its boiler forming one complete unit. By charging the cells alternately, the combustion chamber is kept at a fairly level temperature, with a minimum of variation in the steam pressure of the boiler. An advantage of the system is that one unit can be shut down for repairs without affecting the operation of the others. This method of construction has been largely used by the Horsfall Destructor Company and other makers.

In the common furnace system of construction, only one of the sections, into which the grate is divided, is charged and clinkered at a time, and it is claimed that by charging frequently in small quantities, a maximum temperature can be maintained in the cell itself. The smaller amount of brickwork exposed to high temperatures as compared with the isolated cell system is an undoubted advantage in keeping down the cost of repairs—a serious item in all destructor plants. The common grate furnace is a feature of the "Meldrum" simplex destructor, and a successful installation of this type has been installed at Preston for supplying current to the tramway system. The destructor plants designed by Messrs. Heenan & Froude are constructed on the same principle, but instead of one large arch over the battery of grates, this firm employs a series of small arches arranged parallel to each other. It is claimed that the undulations in the arching produce eddy currents in the furnace chamber, thus mixing the gases more thoroughly and ensuring complete combustion.

The object aimed at is the maintenance of high temperature in the products of combustion utilised for steam raising, and to obtain this it is essential with both types of construction that a large combustion chamber be provided *beyond* the furnaces, where all gases may be finally intermingled and cremated before coming in contact with the boiler. It is quite impossible to ensure that no green or partly burned gases will ever pass into the flues, and it is therefore essential that the chamber should be capable of storing sufficient heat in its brick walls to reduce the disturbance of temperature in the cells during charging and clinkering. The curve (Fig. 2) taken by an electrical pyrometer in the combustion chamber of one unit of the Greenock plant shows clearly the rise and fall of temperature during these operations. The second function of the combustion chamber is to trap as much as possible of the dust liberated from the furnaces, and as considerable trouble is experienced owing to the deposition of dust and grit on boiler tubes, and to the choking of the flues from the same cause, it is desirable to construct the combustion chamber with a settling pit of large capacity, suitable access doors being provided for periodical cleaning.

The position of the boilers with relation to the cells is an important factor in the maintenance of high temperature. In some designs the boiler is sandwiched between two cells, the gases from the fires passing through side openings into a combustion chamber directly beneath the boiler tubes. This design has been largely adopted, and

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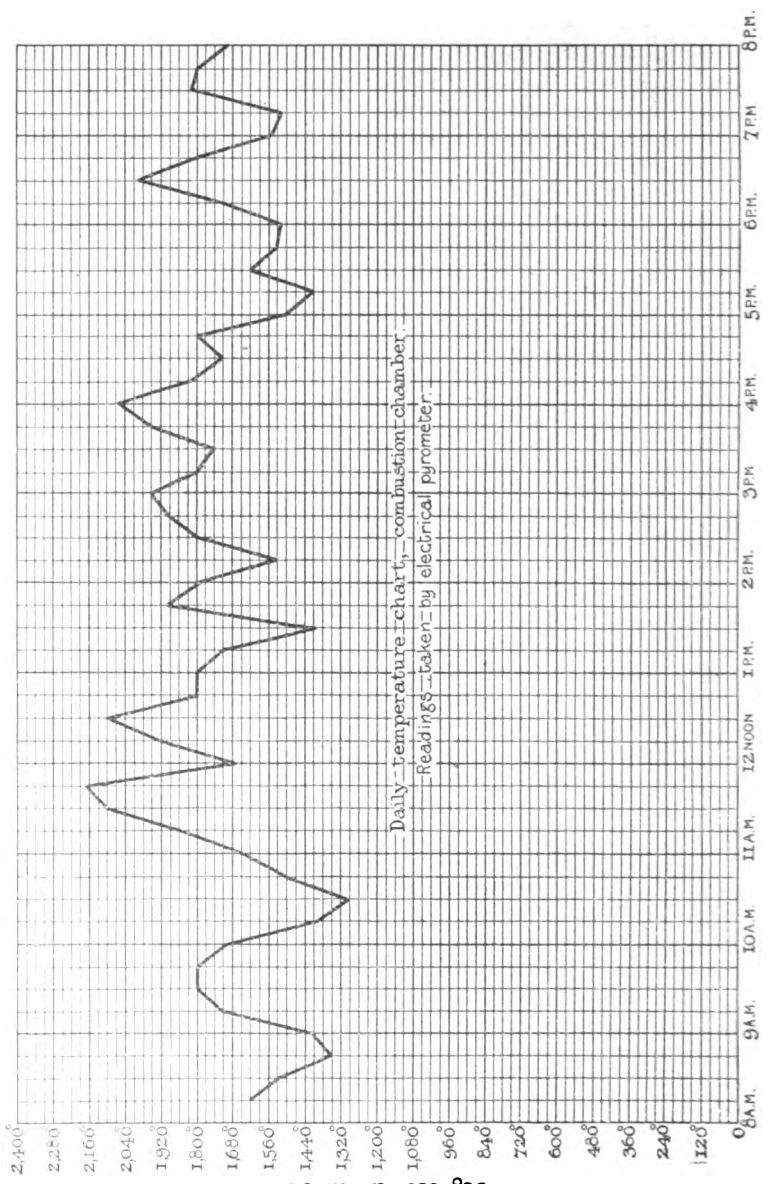

FIG. 2.—Greenock Destructor.

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at first sight it would appear that by bringing the boiler close to the fires the maximum heat available will be absorbed and radiation losses avoided; but, on the other hand, the placing of such a large area of boiler surface at a comparatively low temperature in close proximity to the fires actually tends to retard the process of combustion, and the gases from newly charged refuse coming into contact with the cooler tubes of the boiler may pass uncremated into the flue, and thence to the chimney. The better practice is to place the boiler beyond the combustion chamber, so that the green gases from newly charged refuse in passing through the chamber will combine with a large volume of higher temperature gases, thus becoming thoroughly mixed and cremated before they are brought into contact with the comparatively cool surfaces of the boiler.

Draught and Combustion.—The possibility of utilising destructor heat for steam raising is undoubtedly due to the employment of forced draught for combustion. The large increase in the rates of burning through working at higher temperatures, and the fact that destructors can now be operated in populous districts without giving rise to nuisance, may also be credited to the same cause. Much controversy exists regarding the comparative merits of steam blowers and fan-produced draught for assisting combustion. It is claimed for the steam jet that it is less costly to instal, that the life of the fire-bars is more prolonged, and the process of clinkering the fires less arduous than with fan draught. Another claim, which is sometimes questioned, is, that the steam jets in contact with the hot fuel produce a water gas which is of great value in raising the temperature of combustion. On the other hand, it is admitted that the amount of steam required for the steam jets is from 10 to 15 per cent. of the total steam generated in the destructor boilers against 4 or 5 per cent. for steam-driven low-pressure fans, and that although clinkering is easier, the quality of clinker is more fragile and not so suitable for building purposes.

The advantage of hot-air draught for all combustion processes is generally recognised, and the gain in efficiency by its use in destructor plant is beyond dispute, especially as the added temperature is usually obtained by heat which would otherwise be wasted. By placing a suitable heater in the main flue and passing the air through it before delivery to the furnaces, it is possible to add 300° to 400° Fahr. to its temperature, with a corresponding rise in the temperature of combustion. Another advantage of fan draught is that the air supply can be made to regulate itself to the requirements of the fuel. The amount of carbon in refuse may vary from 10 to 40 per cent., and to ensure complete combustion under all conditions the air supply should be capable of close regulation, and this can be easily attained with fan draught, either by hand-operated valves or by using a separate fan for each furnace driven by a shunt-regulated variable-speed motor. In most installations in this country the average draught pressure employed is from 1 to 2 in. of water column in the ash-pit, but much greater pressures can be employed with suitable fire-bars and thick

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fires. The Greenock plant was originally designed for a pressure of 9 to 12 in., and it was found possible with this pressure to work with fires from 18 in. to 2 ft. in thickness. The fire-grate is formed of solid iron bars perforated with numerous small holes through which the air is forced into the refuse. The experience gained after a few months' experimental working led finally to the adoption of an average pressure of 6 in., which appears to suit the varying conditions as efficiently as the higher pressure, with the advantage of economising the amount of power absorbed by the fans. The type of air heater usually employed consists of a battery of tubes built into the main flue, but in the Horsfall destructor the air is heated by passing it through side boxes in the furnace itself situated between the brickwork and the grate. It is found that their position here lessens the deterioration of the brickwork and assists the process of clinkering, but the author has found in practice that the comparatively small heating surface of the boxes and the rate at which the air must travel through them does not permit of a higher temperature than 180° Fahr. being attained at the outlet, while a further disadvantage is that as the amount of heat imparted to the air depends on the temperature of the furnace, the draught is lowest immediately after charging, *i.e.*, just at the time when high temperature is most needed to dry the refuse and to commence combustion.

An ingenious system of superheating the air draught has been introduced by Messrs. Heenan & Froude in a destructor plant recently erected in Richmond, U.S.A. The furnaces are of this firm's standard hand-fed type, with four grates and divided ash-pits. A secondary chamber is provided below the furnace grate, and, after the refuse has been cremated, the hot clinker is manually withdrawn from the furnace and falls through an opening into the chamber beneath. A fresh charge is then fed into the furnace, and the air required for combustion—which has previously been drawn through an ordinary air-heater in the main flue—is passed through the hot clinker in the chamber before being delivered to the fires. Additional temperature is thus added to the air just when it is most required, and the clinker is also cooled down so that the process of withdrawing and barrowing away is rendered much easier than it would be in the ordinary way.

The employment of fan draught has led incidentally to an improvement in the usually trying conditions under which the men work in the destructor house, as the fan inlet can be carried to the roof, and all dust and fumes drawn into the suction duct, and thence delivered by the fan to the furnace ash-pits. There must always be, even with the best design of plant, a considerable amount of dust given off during the process of clinkering fires, and this improvement in the atmospheric conditions allows of the work being carried out with greater comfort and more expedition than would otherwise be the case.

Boilers.—The two types of boilers in general use for destructor work are Lancashire and water-tube, the latter either of the marine or land type, although in one or two cases the tubular marine type has

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been successfully employed. The Lancashire boiler appears to possess special advantages for destructor installations, inasmuch as its larger steam and water capacity compensate to some extent for the temperature variations due to unequal quality of the fuel. The water-tube boiler, while responding quickly to any rise in temperature, loses its temperature quite as rapidly. On the other hand, it occupies less space than the Lancashire or marine type, and can be more easily kept clean—an important advantage when dust is present in large quantities. Its lower steam and water capacity is a disadvantage in small independent installations, but this becomes less important as the number of boilers increases, and disappears entirely when the plant is used in conjunction with coal-fired boilers. It is usual to provide auxiliary coal-fired grates, with destructor boilers to increase the duty at times of abnormal demand; but the author has found that the presence of hot gases from the destructor furnaces retards the process of coal combustion, and the actual benefit of the auxiliary coal-fired grate lies in the use which can be made of it when, through any reason, the destructor furnace is out of action. The experiment of forcing the boilers by mixing a charge of refuse with a smaller charge of coal in the destructor furnace was not a success, for on cleaning out the fires the coal was found only partially burned, the remainder being embedded in the clinker, which had apparently protected it from combustion.

The economy due to superheating steam is universally recognised with coal-fired boilers, and as the destructor boiler plant in combined works is generally situated some distance from the engine-room, the losses from steam-pipe radiation are comparatively great. It is possible, by superheating, to ensure that at least dry steam only will be delivered at the engines, while the losses through drains and steam traps are materially reduced.

In the Greenock installation the marine type of water-tube boiler is employed, and the hot gases from the destructor are passed once through the tubes in an upward direction, the superheater being placed between the upper and the lower sections. The temperature chart, Fig. 3, shows what might be called three stages in the manufacture of steam for use in the engines. First, the temperature of the hot well about 90° Fahr. after condensation of the exhaust steam, thence after delivery by the pumps the feed water is raised to a temperature of about 300° Fahr. in the economiser by the flue gases, and then passed through the boiler, where it is evaporated into steam at 200 lbs. pressure, and finally through the superheater, being delivered from the latter at a temperature of about 550° Fahr. The distance between the destructor boilers and the engine stop-valve is about 100 ft., and it is found that in travelling through this distance the average temperature loss at normal full load is 40° Fahr.

The high outlet temperature at the economiser gives the impression that full advantage is not being taken of the available heat in the boilers, and it might be possible by providing baffle walls in the boiler

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FIG. 3.—Greenock Destructor.

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sections to absorb more heat in steam raising, and so reduce the temperature of the gases in the main flue; but from experiments made in this direction it is doubtful whether any real advantage would accrue. The reason appears to be that the dust which collects around the baffle plates and which can only be partially removed by cleaning while the boiler is under duty, reduces the available heating surface, with consequent reduction in the capacity and efficiency of the boiler. This question of dust in destructor flues and boilers has not always received the special attention by designers that its importance deserves, and the poor results obtained in many combined stations may generally be traced either to imperfect design of combustion chamber and flues or to insufficient space being allowed for dust settling.

However perfect the design of destructor furnaces, good results can only be attained if proper methods are employed in managing the installation. In coal-fired boilers, stoked by hand labour, we know that the efficiency may vary by as much as 20 or 25 per cent. with a change in the men employed. The importance of the stoker is, therefore, much greater when low-grade fuel such as town's refuse is dealt with, and to obtain continuity of temperature the most careful attention has to be given to the strength of air blast and the management and spreading of the fires. If the fires are allowed to blow into holes an immediate cooling effect takes place, and one reason for the difference between results obtained on trials and the average results over a longer period is probably the careful expert supervision —generally by the maker's representative—when test runs are being made. In burning refuse with heated air it is possible, if the fire is not carefully managed, to produce the appearance of perfect combustion on top of the fire, while the under side next the fire-bars does not rise above the temperature of the incoming air. To overcome this the fire requires to be "managed," and so far the only method of doing this is by careful mixing and stirring of the refuse while it is burning.

It has been said that the best clinker is produced when the cells are also worked to the greatest advantage for steam-raising purposes; but the author's experiences does not confirm this opinion, as he has found that with most classes of refuse a hard clinker cannot be produced unless the material is kept burning for some time after the maximum temperature has been attained, whereas for steam-raising purposes it is desirable that the maximum temperature should be attained as rapidly as possible, and the products of combustion withdrawn from the fire before the cell begins to cool down.

Supervision.—There have been differences of opinion, in many cases, as to which department should supervise the working of the destructor, but from the experience already gained it is now generally admitted that if the best results are to be obtained, the department which is responsible for utilising the steam should also control its production. It should not be overlooked by local authorities that the successful management of a modern destructor plant require quite as much care as a coal-fired boiler installation, and it is therefore necessary that the

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management and working of the plant should be in the hands of those who possess the requisite training and experience to fit them for this work.

Financial Results.—The value of destructor steam to the electricity undertaking is a subject which has caused the widest difference of opinion. On the one hand we have the exaggerated estimates of the enthusiast—not always a destructor maker—and on the other the oft-repeated opinion from station engineers that the combination is unsatisfactory in practice and valueless in results. The truth, as usual, appears to lie between extremes. There is no doubt whatever that the calorific value of ordinary town's refuse is sufficient to produce a considerable amount of steam if burned under proper conditions. In Liverpool, where 600 tons of refuse are burned every day, no less than 9,209,369 units were generated from destructor steam during 1907, and this result has been obtained with non-condensing compound engines, using 50 lbs. of steam per kilowatt-hour. In other towns where the destructor is linked with the electricity undertaking equally good results can be shown, and it is somewhat significant that the returns in the *Electrical Times* Table of Costs prove that in most cases the fuel costs of combined stations are lower than in similar stations run entirely on coal. In view of the assertion frequently made that the destructor is a burden on the electricity undertaking, it is interesting to find that in the Metropolitan districts the lowest fuel costs are claimed by Hackney, a combined station; while amongst smaller provincial towns another combined station—St. Helens—has long been noted for its low fuel cost per unit. The Liverpool undertaking, which returns 0·35d. per unit as its total fuel costs, only pays the Cleansing Department 0·2d. per unit for the 9,000,000 units generated at the destructor stations. At Partick, the first combined station in Scotland, the fuel costs were remarkably low for some years, the minimum figure of 0·20d. per unit sold being returned for 1905–6, when the bigger undertaking in Glasgow, with ten times the output, could only reach 0·23d. per unit. These facts give the impression that while in some cases the value of the destructor steam may be overestimated, there are others in which it does not receive its due share of credit.

The various methods employed in combined stations to determine the value of the destructor steam have been the subject of much contention. The problem is rendered more difficult by the fact that all the boilers usually deliver to a common steam main, and that no accurate device exists at present for the measurement of live steam. Special tests for short periods to show the evaporation of water per pound of refuse burned are of little value owing to the varying quality of the materials dealt with, and electrical tests on the basis of units generated, which are possible in those works where the generators can be run exclusively from destructor steam at certain periods of the day are also doubtful, as they do not take into account standby losses and other factors which affect continuous working results. The only true basis is, of course, the cost which

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would be incurred if the generating plant were run from coal alone under similar conditions as regards demand and output. To make the comparison accurate, any saving in capital cost to the electrical undertaking should be taken into account, and while it is rare to find any credit allowed to the destructor on account of saving in labour, there is no doubt that in most cases a saving does result to both departments due to combined supervision.

To take the saving in capital cost first, both departments will benefit from the obvious fact that the cost of a site for a combined undertaking is less than two separate sites. In buildings there is also an appreciable saving, and as one chimney will serve both undertakings, the cost will be halved to each. The saving in boilers is not so important as it appears, as it is necessary to provide a sufficient capacity of coal-fired boilers to guard against an interruption to the working of the destructor plant in winter when snowfalls may interfere with the delivery of refuse, but the saving in maintenance and repairs should be considered. In feed pipes and piping there is a distinct gain through combination. In all these items the capital cost should be fairly apportioned between the departments, and any saving to the electricity department taken into account when adjusting the actual value of destructor steam.

In the combined installation at Greenock the difficulty of arriving at the steam value of the refuse was rendered easier through the generating station having been run exclusively by coal-fired boilers for three months before the destructor commenced working, and it was therefore possible to ascertain exactly the consumption of coal per unit generated and the efficiency of the boilers and generating plant. Separate water meters had been installed to register the evaporation in each set of boilers, and it was intended to apportion credit on this basis, but this method did not take into account the standby losses incurred through the irregular working of the destructor, and it was also found, on starting the destructor plant, that increased radiation losses from the steam pipes due to the position of the destructor boilers brought up the consumption of steam per unit generated from 24 lbs. to 26½ lbs. It was considered only fair that the destructor should be debited with these losses, and it was therefore decided to apportion the units generated on the basis of the actual consumption of coal before the destructor commenced working, and the results given later may therefore be taken as the true value of the steam to the electricity undertaking under present conditions. The allocation is based on a consumption of 4½ lbs. of coal per unit generated, and the weekly coal consumption divided by this figure gives the number of units to be apportioned to coal-firing, the remainder being credited to the destructor. The average price of coal has been taken at 10s. per ton, and after including an allowance for capital charges on boilers and pumps, the figure of 0·35d. per unit was arrived at as a fair payment to make to the cleansing department for steam.

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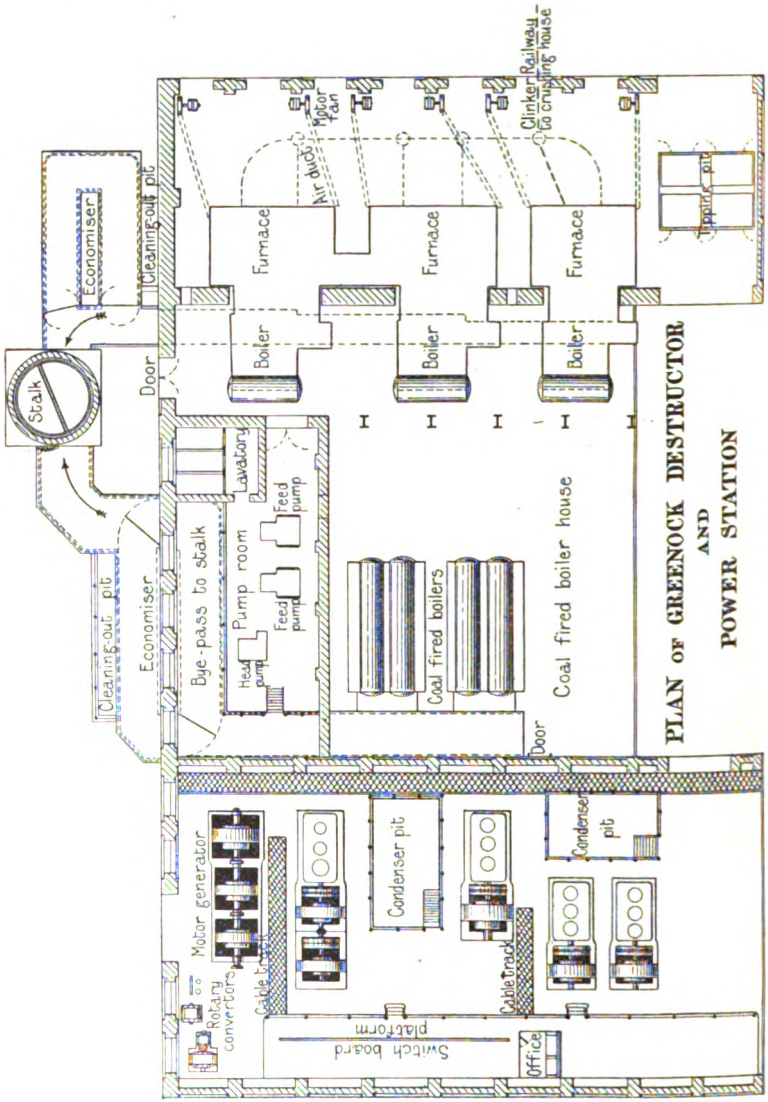
In preparing this paper the author intended originally to tabulate the results obtained from a number of combined works, but in



PLAN OF GREENOCK DESTRUCTOR AND POWER STATION

FIG. 4.

gathering information for this purpose he found that so much difference exists in working conditions and in the methods of arriving at the value of destructor steam, that a comparison might be

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misleading unless all the circumstances of each case were known. He therefore proposes to confine this section of the paper to the results obtained from the plant under his charge, where special care has been taken during the past year to obtain accurate records.

Fig. 4 is a plan of the combined electricity and destructor works at Greenock. It will be seen that the buildings have been arranged in four bays, the destructor plant occupying the west bay, the east bay, which is the largest, forming the engine-room, while the two centre sections contain the destructor boilers and coal-fired boilers. Clinker

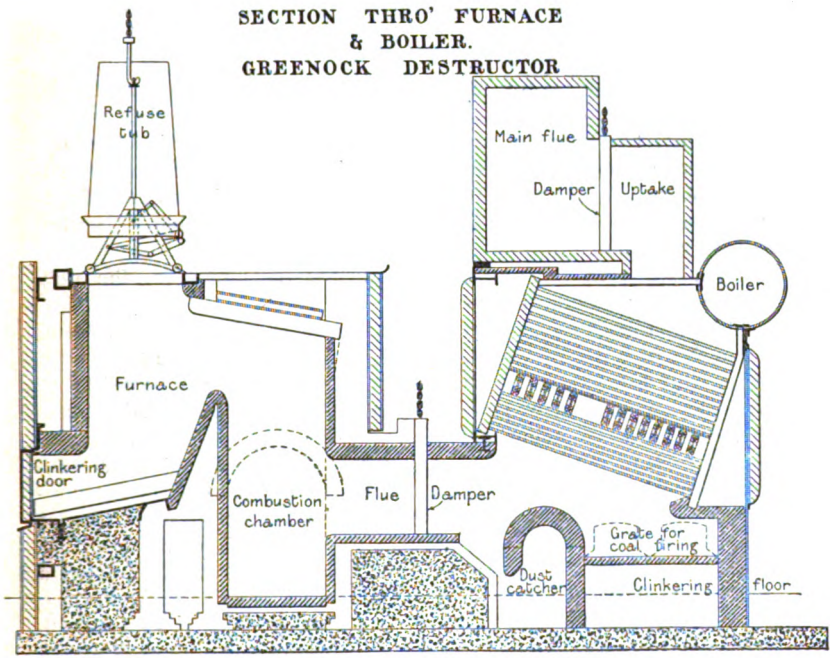

FIG. 5.

treatment machinery has been installed in a separate building to the west of the main building.

The destructor consists of six cells and spacious combustion chambers, arranged in pairs, each pair forming, in conjunction with a water-tube marine-type boiler, a complete and independent unit. Fig. 5 is a section through furnace and boiler. The furnace grates, which slope from back to front, have each an area of 25 sq. ft., and are sufficient to burn one cartload of refuse at a charge. The high-pressure air blast is obtained from electrically driven variable-speed fans, one to each furnace. The fan motors are totally enclosed and

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are controlled from a position near the clinkering door of the furnaces, an automatic device being provided which stops a fan when the corresponding furnace door is opened for clinkering. The clinker, when withdrawn from the furnace, is conveyed by an overhead railway to the crushing mill, where it is broken up and screened. Auxiliary steam jets have also been provided, but are only used in the event of a breakdown in the fan system. A special dust catcher has been built into the main flue between the combustion chamber and boiler. The boilers are fitted with auxiliary grates for coal firing. In case of a breakdown to a boiler the whole of the furnace gases can be bye-passed from the combustion chamber direct to the chimney. A bye-pass has also been fitted to the economiser between the main flue and the chimney. The chimney is 150 ft. in height, 10 ft. internal diameter at the base, and is firebrick lined throughout.

A 10-in. main carries steam from the destructor boilers to the main range near the wall of the engine-room, and the feed piping is designed to allow the destructor boilers to be supplied through their own economiser or from the hot feed-water main of the coal-fired boilers. A Kennedy hot-water meter is provided to each feed-water main, and automatic CO_2 recorders and draught gauges are fitted on each main flue.

In addition to the destructor plant the installation at the new Greenock works comprises :—

Two double drum coal-fired boilers, each capable of evaporating 16,000 lbs. of water per hour. These are fitted with close link chain grates and mechanical stokers. The generating plant consists of two 750-k.w. and two 400-k.w. direct-current Belliss-Westinghouse sets, one of these being arranged as a two-machine balancer and the others as single machines at 500 volts. The large sets on test with steam superheated to 500° Fahr., and a vacuum of 26 in. at the condenser consumed 17·8 lbs. of steam per kilowatt-hour, and the smaller sets 18·5 under the same conditions. Two surface condensers are employed, the cooling water being obtained by gravitation from a reservoir built on the course of an aqueduct which originally ran through the site, the water being then employed to operate a mill. Under normal working conditions the average consumption of steam is 26½ lbs. per kilowatt-hour, this figure including all losses. All auxiliaries are electrically driven. The coal used has a calorific value of 11,600 B.Th.U., and the consumption, as already stated, averages 4½ lbs. per kilowatt-hour. The units used on works for feed pumps, mechanical stokers, air pump and economiser (not including units used on destructor) amount to 1·9 per cent. of the generated units. The chart Fig. 6, shows the total output of the works during twelve months ending January 31, 1909, the shaded portion representing the proportion generated by destructor steam, and the lowest line the amount of energy used by the destructor for power and light. The latter amounts to 12 per cent. of the destructor generated units divided as follows ;—

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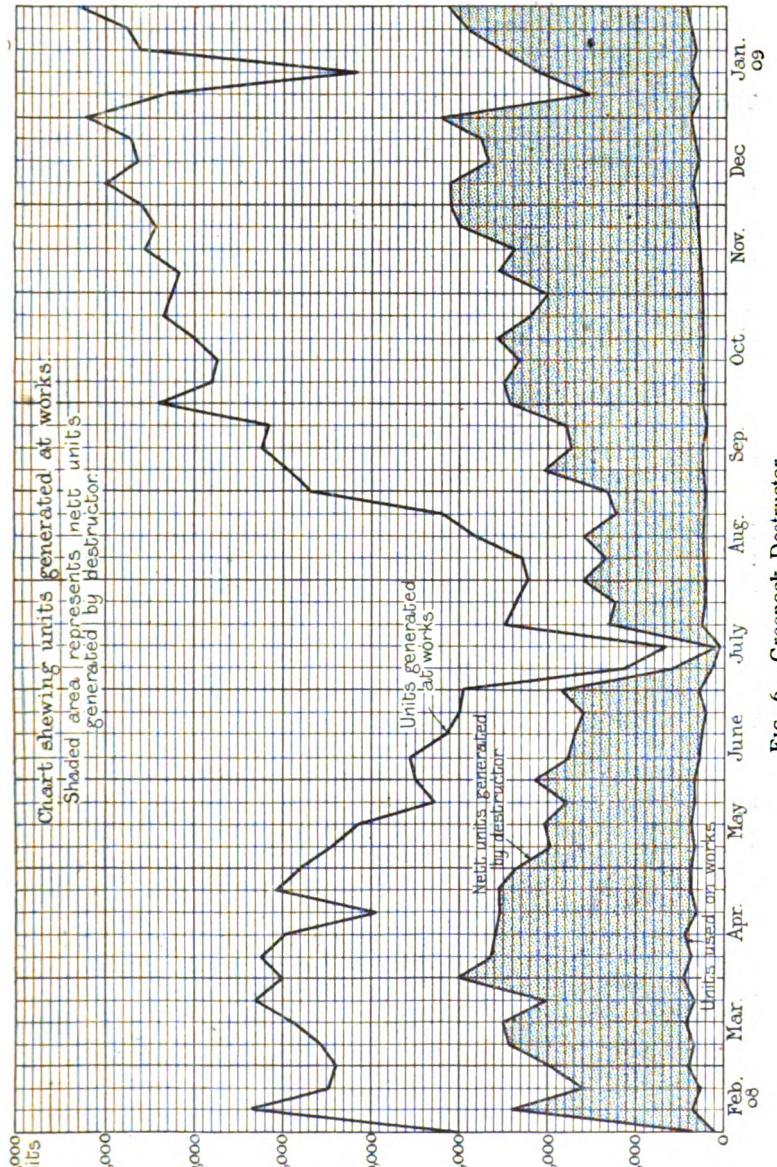

FIG. 6.—Greenock Destructor.

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Fan draught	8·5 per cent.
Cranes	1·0 „
Clinker treatment	1·4 „
Lighting	1·1 „

The amount used for fan draught is unusually high, and is brought about by the abnormal pressure employed, but it is fully expected that this figure will be reduced by at least 10 per cent. in future.

The price to be charged to the destructor for energy supplied is a further point of contention, but the proper way is undoubtedly to treat the destructor in exactly the same way as another consumer with a similar load factor, due allowance being made for the absence of distribution costs. On this basis the price arrived at was 0·6d. per unit, the load factor being estimated at 35 per cent.

It has been mentioned already that tests over a short period of time are of little use to determine the true value of destructor steam. As an indication of the capacity of the destructor such tests are, however, of some importance. The following is one of the three tests made on the Greenock destructor, and it is interesting to note the difference between these results and the average results as shown by the year's returns. It will, no doubt, be pointed out that higher results than 96 units per ton have been obtained from tests on hand-fired destructors, but it should be borne in mind that the system introduced at Greenock was adopted primarily on sanitary grounds, steam raising being regarded only as a secondary object. On the other hand, the average result of 67 units per ton over a whole year's working is higher than any authenticated figure which has come under the author's notice up to the present, and as it includes all standby losses on the station, may be considered extremely good. It is only fair to the makers to state that the installation was in some respects a new experiment, and that the results during the first part of the year were adversely affected by want of experience on the part of the workmen employed. It should further be explained that the repairs bill is chiefly made up of alterations and experiments carried out to improve the working of the plant after it had been taken over by the Corporation.

The cost of carting away unsaleable residue is at present a large item in the revenue account, and the labour charges for crushing and screening clinker as compared with the return from clinker sold are abnormally high, owing to the difficulty of finding a market for these materials in the present depressed state of the building trade.

Test Report.

Date of test	October 29, 1908.
Duration of test	8 hours.
Number and type of cells	4 cells, "tub-feed."
Total grate surface	80 sq. ft.

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System of forced draught	High-pressure fans.
Ashpit pressure	4–6 in.
Nature of refuse	Household and trade refuse.
Men employed	2 stokers, 1 craneman, 1 leading hand.
Number, size, and type of boilers...	2 Babcock and Wilcox, 2,070 sq. ft. H.S.
Economiser, No. of tubes (Green's)	240 tubes in 2 sections.
Total quantity of refuse burned ...	32 tons, 5 cwts.
Ditto per cell per 24 hours ...	24·72 tons.
Ditto per square foot of grate per hour	103 lbs.
Total water evaporated	8,050 gallons = 86,500 lbs.
Total water per square foot of heating surface per hour	2·43 lbs.
Total water per lb. of refuse burnt (actual)	1·11.
Total water per lb. of refuse from and at 212° F. or 100° C. ...	1·41.
Mean steam pressure	195 lbs., superheated to 564° F.
Mean feed temperature	91·5° F. entering economiser.
Total electrical units generated ...	3,101·5 units.
Electrical units per ton of refuse ...	97 units per ton.

Capital Expenditure.

Capital cost of destructor, including one-half cost of site, one-half of chimney, buildings, furnaces, plant, economiser, proportion of steam and feed piping. Total	£19,800

Financial Results at Greenock Destructor for Twelve Months Ended January 31, 1909.

Revenue Account.

Expenditure.

	£	Per Ton. s.	d.
Labour—			
Operating destructor	936	1	1¼
Treatment of residue	134	0	2
Repairs—			
(*a*) Buildings...	40	0	2¼
(*b*) Plant	120		
Disposal of unsaleable residue	135	0	2
Power and light	330	0	4½
Rates, taxes, insurance	83	0	1¼
Management	65	0	0¾
Total	£1,843	2	2

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Credit.

		Per Ton.
Sale of steam	1,665	
Sale of clinker	65	
	1,730	2 0¼
Balance to Net Revenue Account	113	0 1¾
Total	£1,843	2 2

NET REVENUE ACCOUNT.

Interest on £19,800 at 3½ per cent.	696	0 9¾
Sinking fund, $\frac{1}{30}$th of capital	663	0 9¼
Balance from Revenue Account	113	0 1¾
Net cost of disposal... ...	£1,472	1 8¾

Technical Records.

Tons of refuse destroyed	16,095
Units produced from destructor steam	1,142,064
Units used for power and light	132,006
Units generated per ton	67·2
Total clinker produced...	5,338
Total clinker sold	1,286

The author is aware that there are phases of the question which have not been dealt with in the paper, but trusts that the arguments and figures submitted may elicit information from other engineers on this important subject. The conclusions arrived at may be summarised as follows:—

(*a*) That, given a suitable design of plant, ordinary town's refuse may be destroyed at a combined works without giving rise to nuisance troubles, always provided that the sanitary object of the destructor is considered of primary importance.

(*b*) That where local conditions permit the steam to be utilised for at least 9 hours per day it will be a distinct financial advantage to combine the electricity works with the refuse destructor.

(*c*) That a combined scheme should only be undertaken after careful investigation and under expert advice.

(*d*) That in the interests of efficiency the combined installation should be under the control of the electrical engineer.

(*e*) That the financial adjustment between the electricity and cleansing departments should be made on the basis of value supplied, including saving in capital expenditure and labour costs (if any).

The author has to acknowledge his indebtedness for information regarding various types of plant from firms whose names have been referred to in the paper.

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Discussion at Glasgow, April 13, 1909.

Mr. W. W. Lackie (Chairman): I must confess that I am of opinion that a refuse destructor is a dust constructor, and while Mr. Robertson has made out a perfectly good case for Greenock, I believe that in a city like Glasgow it is impracticable to combine the generating stations and refuse destructors. When we consider that there are 7 destructors, it would mean 7 sites, 7 stations, and 7 staffs of men, and the extra capital of the plants and labour would quite counterbalance the saving in fuel. It is very easy to be wise after the event, but it appears to me that the only proper use of destructors in Glasgow would be to supply steam and hot water for the public baths, and that would save a great deal of money. With regard to the method of charging the furnaces, it struck me that a chain-grate stoker would be advantageous, and would save all the handling that the author has described. I know that many stations have reduced their fuel costs in refuse destructors, but it seems that expensive condensing plant has been put in, and that the increased capital charge far more than outweighs the saving. The total horse-power will amount to about 1,800, and with 50,000 H.P. to be supplied, the real state of affairs in Glasgow will become evident. The cleansing department have available 300 H.P. for use, 150 of which is for working machinery in the destructor. Another way of looking at it is that in Greenock Mr. Robertson seems to have generated $\frac{1}{3}$ of his units from destructor refuse, and $\frac{2}{3}$ from steam, but in Glasgow we generate only about $\frac{1}{10}$ from destructor refuse, and $\frac{9}{10}$ from steam. Mr. Lackie.

Mr. F. A. Newington: Two or three months ago I had the pleasure of seeing over Mr. Robertson's combined destructor and electricity works at Dellingburn Street, and I found an absence of dust and smell. The arrangements for handling refuse seemed to be very complete, and this method of lifting the refuse by means of tubs, and tipping them, was an enormous advance over the arrangements in old destructors that I had seen. On the whole, the works were quite as clean and free from dust as generating stations without any destructors, so that the trouble with dust and dirt may evidently be got over. I quite agree with what he says about drying the refuse. He refers to thermal storage, and it seems that in a destructor where the quantity of steam produced is more than the amount of electricity required during the day, thermal storage should prove very useful. The arrangements at Wood Lane and at Knightsbridge seem to be excellent, but the method has not been generally adopted, although it appears very suitable. It seems rather a pity that the auxiliary coal grate cannot be made a success, because if the troubles could be got over it would do away with the necessity of having additional boilers, and so would save capital outlay. With reference to the combination of electricity works and refuse destructors, I agree with the Chairman that for places with a large day load it seems of little value, although for towns where the steam produced by the destructor will do the greater Mr. Newington.

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Mr. Newington. part of the day load, it is probably an advantage to combine the two. I think in combined stations the value of the steam generally seems to be underrated. In Liverpool we see the price paid is only 0·2d. per unit, as against 0·25d., which is the actual cost, but I daresay the low price is due to careful management of the furnaces, as explained on page 663. On page 656 the author talks of one craneman being employed for eighteen hours, but I should like to know where he can find such a man. In the financial results on pages 671 and 672, the net cost of disposal is £1,472 for the year, and it would add considerably to the value of these figures if the author could also state what the extra cost would have been of carting to the original tip for that quantity of material. That would give us an idea of the comparison between the present cost of disposing of the refuse and the old arrangement of tipping.

Mr. Mavor. Mr. SAM MAVOR: It is interesting to know that one is responsible for the production of about 2 lbs. of combustible refuse per diem. and through the destructor, for about one-tenth of a unit, so that this society, with about 200 members, is collectively responsible for the generation of about 10 units. There can be no doubt that cremation is the ideal method of getting rid of refuse, but it is clear that in such a city as Glasgow it is quite impracticable to combine it with the generation of electric power, although in small towns like Greenock, where the radius of carting is within limits, it can, as Mr. Robertson has shown, be very effectively combined with electrical production. Another point which has struck me from a social point of view, is that the refuse, as regards calorific value, comes from the poorer districts, showing that the poor in this, as in many other things, get less value for the money they spend than those who know better how to guide their gear. It also occurs to me that there must be some good reason why the chain-grate stoker or other mechanical apparatus is not used. It seems incredible that such material has to be dealt with by hand firing. That is a process that one would think should really be taken out of the region of manual labour.

Mr. Evans. Mr. W. T. EVANS: I would like to ask a question as to the calorific value of this fuel. Is not the value of the fuel largely due to cinders and unburned coal, and would you get any steam at all from town refuse not containing them?

Mr. Willis. Mr. R. H. WILLIS: I notice that in July Mr. Robertson had 210 tons of refuse, from which he obtained no units, yet in August he had only 230 tons of refuse, and he obtained 50 units. Is it because there was no demand for electricity in July, and therefore the hot gases were diverted up the flue? Another question that I would like to ask is on the subject of forced draught. I notice that throughout the paper forced draught is used for the purpose of firing; it seems to me that that is a great disadvantage. When the door is opened a great deal of dust is blown out on the firing platform, and surely the use of induced draught would overcome the whole of that difficulty. Instead of dust being blown into the firing platform, it would be kept

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inside the chamber, and I would like to know whether this has been tried in connection with refuse destructors. Mr. Willis.

Mr. J. H. BOWDEN (*communicated*): Being connected with an undertaking at present in the constructional stage as regards utilisation of steam from a dust destructor adjoining the electricity works, I have been interested in Mr. Robertson's paper, and there are a few points on which I should like some information. The demand for energy at Poplar is such as to enable the undertaking to take a continuous supply of 10,000 lbs. of steam per hour over twenty-four hours of each working day, with an increased quantity during peak loads, if available. These conditions, I take it, from the author's point of view are ideal. The difficulty caused by the presence of dust and grit in the engine-room will be avoided, as the destructor boiler house and the electricity works require a considerable length of steam main to connect up the one with the other. I regret to hear that Mr. Robertson has experienced difficulties in burning coal with refuse, and shall be glad of further details. This matter, to my mind, is most important, as the value of a destructor for steam raising is considerably diminished, if reliance cannot be placed upon a regular stipulated quantity being supplied, and in order to carry this into effect recourse must at times be had to coal firing in case of failure in the quality of refuse. Without actual knowledge of the working results at Greenock, the author's statements appear to be contradictory. It is difficult to reconcile with this the statement that the best quality refuse is that "richest in carbon from the ash-pits in the working-class district." It is evident that partly burned coal is referred to, therefore fresh coal should provide better results. Is it that the low grade coal or coke dust is inferior to the refuse? If so, would not a higher grade coal give the desired results? I am quite in accord with Mr. Robertson as to the value of the air heater, and Messrs. Horsfall have arranged to instal a separate regenerator on the Poplar installation, as it is most essential that hot air should be available at those times when the temperature is lowest on charging the furnaces. I also agree that a great saving can be effected by proper methods of stoking, but I should like some indications of the manner in which fires should be "managed." How often should the refuse be carefully mixed and stirred whilst burning? Does not this method entail a considerable loss by cooling, nullifying, to a great extent, the benefit derived? Mr. Bowden.

Whilst the strictures on estimating the value of steam derived from this source are very sensible, I think the author has, to some extent, failed in putting his opinions into practice. It is certainly correct to assume that the primary object of a destructor is the destruction of town refuse, and the supply of steam must be treated as a by-product, which will cheapen the process. If steam can be raised in this manner and supplied to an electricity undertaking at a cost not more than would be entailed by the use of coal fuel, and, at the same time, be a source of income to the borough or corporation, it is undoubtedly the correct policy of the Council to adopt such methods. The author

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Mr. Bowden.

shows us that he has reduced the cost of destroying refuse to 1s. 8¾d. per ton, an exceedingly low figure, but he does not inform us of the cost prior to the installation of the combined plant. Has he not brought this about at the expense of electricity supply? If so, the system is wrong in principle, as the electricity consumers are being taxed for the benefit of the general rate. The payment made by the author is 0·35d. per unit generated, and if we assume an efficiency of distribution of 80 per cent., the cost per unit sold is 0·4375d. Surely this is too high for Greenock, when in Poplar, with high railway rates, the figure per unit sold for coal alone was 0·35d. during 1908–9, and, with the present low prices for coal, this figure has been reduced to 0·25d. per units old. Taking the basis adopted by Mr. Robertson—viz., 4½ lbs. of coal at 10s. per ton—we get a result of 0·241d. for coal alone. How is the remaining 0·109d. apportioned? This represents a sum of £519 on the annual output, and, on Mr. Robertson's own showing, the capital value saved is small; labour also cannot be great, and I take it that water is charged entirely to the electricity department.

Again, in determining the coal figure, we find that the electricity plant-generated energy with an average steam consumption of 24 lbs. per unit—an exceptionally good figure—or 5⅓d. lbs. of water evaporated per lb. of coal of 11,600 B.Th.U. value. I shall be glad if Mr. Robertson will confirm this figure, as we might reasonably expect 7 lbs. of water per lb. of fuel of this calorific value, especially with the latest type of chain-grate stokers, as installed at Greenock in keeping with generating plant of exceedingly good efficiency; 3½ lbs. of coal per unit at 10s. per ton is equal to 0·188d., and with the addition of 0·062d. or £295 per annum for capital and other charges, a payment of 0·25d. would, in my opinion, be ample. It is important to carefully consider, in fixing the charge for destructor steam, that the basis price of coal should be a mean figure. Coal, like most commodities, fluctuates in price to a considerable extent, and it is not desirable to alter the rate of charge for steam. According to market price of coal, 10s. per ton, I take it, is considerably above the mean value of coal of 11,600 B.Th.U., delivered into bunkers at Greenock. Has the author considered this phase? I would further point out that, although he refers to standby losses, he has not taken these into consideration in fixing the charge. In order to give full effect to destructor steam, the electricity department should be prepared to take *all* the available product. That is to say, the destructor units would be represented on the load curve by the bottom of the load, and all fluctuations would be borne by the electricity steam plant. The expense, therefore, of banked boilers, which is distributed over the whole output of an independent station, would be doubled per unit when equal proportions of the output are derived from both sources of a combined undertaking. This is a loss entirely independent of that referred to by Mr. Robertson due to increased radiation losses from steam pipes from destructor boilers.

I do not altogether agree with Mr. Robertson's conclusions regarding the method of charging for the supply of steam. I take

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Mr. Bowden.

it that, if we assume an output of 75,000 units, and a coal consumption of 100 tons, the allocation would be, in round figures, 50,000 units to the electricity department and 25,000 to the destructor; but, supposing Mr. Robertson bought a lower grade coal at 8s. per ton, and raised the consumption to 5 lbs. per unit (a distinct gain to the department) the destructor would lose the value of 5,000 units by the transaction, and, if a higher grade coal were bought, the loss would be on the other side. I believe that steam-measuring apparatus can be procured. Will Mr. Robertson state if he has experimented in this direction, and if he has tried the "Sarco" steam meter? Surely, if he is buying steam, not units, there is some better method to be adopted than the crude system he lays down. Would not the measurement of water fed to destructor boilers, with due allowance for blowing down at regular intervals, be more effective? Certainly the percentage of error would be considerably less than by his present system. I agree as to the method of charging for energy, but I think a lower rate than 0·6d. could be reasonably charged, if the destructor shut down all plant not necessary for steam raising over the mid-winter peak, and so raise the load factor to 50 or 60 per cent.

Mr. Leask.

Mr. H. N. Leask (*communicated*): I am glad to find that at least one electrical engineer has come forward to support the proposition that under certain conditions appreciable benefit can be obtained from the combination of electricity works and refuse destructors. I entirely agree with Mr. Robertson in his premises, the first and most important being that there should be a steady demand for energy at the eletricity works: the second, that the refuse should be collected daily, but in addition to that I think it should be collected as far as possible from all parts of the area daily in order to ensure that the daily quality and quantity of refuse should be the same; and the third, that the refuse should be capable of quick transfer from the collecting carts to the furnaces. The importance of this latter may, however, be exaggerated. With refuse collected daily in a climate such as ours, there is no fear of such rapid putrefaction as would necessitate the immediate tipping of refuse into the furnace. I also agree with Mr. Robertson on the general proposition that the refuse should be burned over the greater portion of the twenty-four hours. This ensures greater efficiency of the furnaces, lower capital outlay, and reduction in standing charges.

Had each plan for combining a refuse destructor and electricity works been carefully considered on its merits, with due regard to local conditions, such as price of fuel, quality of refuse, and especially the nature of the demand in the power station, there would have been fewer disappointments, but within recent times this reproach has been removed; at least one firm keep a highly trained staff whose duty it is to consider the proposition on these lines, and to go even further and ascertain the quality of the refuse which has to be dealt with. Such a proceeding has been of great value to those purchasing installations from the firm, for in every case the undertaking has produced a saving in cost superior to anything heretofore achieved, and the authorities have

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Mr. Leask. been greatly pleased because the guarantees were not alone achieved but exceeded. It has enabled that firm to guarantee the evaporation with great accuracy, and I feel sure that Mr. Robertson would be very pleased to have an average of over 1 lb. of water throughout the year instead of the ¾ lb., which he appears to have obtained, and in the winter-time, when this load is greater, considerably over 2 lbs. It might be said that such a result could only be obtained with refuse of exceptional quality, but this is not so. Refuse obtained from the centre of a colliery district and that obtained in the centre of an agricultural district with a very mild climate have both given astonishing results—viz., in the colliery district, 2¼ lbs. in winter and 1½ lb. in summer, and in the agricultural district, 2 lbs. in winter and 1¼ lb. in summer. This result is due to the arrangement of the plant and adjuncts, and also in a great measure to the method of feeding the furnaces. I am glad that Mr. Robertson recognises the great disadvantages of the tub feed system. It prevents any selection or proportioning of the charges, and the depositing of a cartload of refuse into the furnace necessitates a reduction in the temperature and consequent variation in the steam pressure. Most combustion engineers know that nearly every kind of coal needs to be charged differently, at a different rate at different parts of the furnaces, in different thicknesses, and so forth. It is evident that this is more necessary when dealing with heterogeneous fuel, such as town refuse. It would appear that whilst the reduction in temperature due to the increase of cold air is largely eliminated by this method (tub feed), there is a corresponding reduction due to the cooling effect of the charging of a large mass of refuse at a time. Even such a good fuel as coal would not stand this handling, and the proof of the pudding appears to be in the eating, for were it not for the extraordinary economy of the Greenock station the units of electricity recovered would have been insignificant.

I take issue with Mr. Robertson on the question of the saving in labour on a plant of 100 tons capacity, and think it doubtful whether it can be done by one crane man in 18 hours. On the question of the reduction in temperature during charging, I would point out that glass furnaces are worked continuously with their doors open, and consider it quite feasible to erect a refuse destructor in the same manner. My firm have carried out one installation, and hope to carry out many more, in which it will be a matter of comparative indifference whether the doors are open or closed. With regard to the claim of cleanliness, there can be no doubt that the system looks very attractive, but with the daily collection the refuse which is handled by the housemaid in the morning in the house could surely be handled by a skilled labourer in the afternoon of the same day without fear that the man would be contaminated. It is surely not right for the sake of the appearance of a destructor installation employing some dozen men, to expose the whole town to the dissemination of a lot of unfixed volatile matter, which must surely occur, as Mr. Robertson points out that there is a great fluctuation of temperature when a cartload of

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refuse is at one operation charged into a furnace. I know at least one firm that would guarantee the Greenock Corporation an average of three times the evaporation that they appear to have obtained, and that at a reduced charge, taking into account labour, maintenance, and capital cost. I am pleased to note that Mr. Robertson recognises the disadvantages of the system of air heating adopted at Greenock, but he does not go far enough. There is no economy in this method, except so far as it may tend to the reduction of the total air entering the furnace, heat being taken from the furnace at the most vital point, and the effect being practically *nil* immediately after charging. My firm have erected a plant where at the moment of charging and for some 15 minutes thereafter the air enters the furnace at a temperature of 1,000° F., but in these islands it would not be worth the capital outlay entailed to obtain such a result, although it might be in cases where a ton of refuse is deposited in the furnace at one time. Mr. Leask.

I heartily endorse Mr. Robertson's statement that however perfectly a destructor furnace may be designed, good results can only be obtained when the installation is properly managed. There is no doubt that a destructor needs to be well managed, and even sympathetically handled, if such an expression can be used, and were this done on a greater scale many towns might congratulate themselves on their foresight in combining the two installations. Surely Mr. Robertson will agree that if the careful expert supervision of the maker obtained very superior results it would be worth while for the Corporation to have expert supervision all the time. If the makers could obtain such excellent results there is no reason why the authorities should not obtain equal, and possibly better results, because short tests are usually made with men more or less raw to their work and before the furnaces have thoroughly settled down to their duties. The liberal manner in which Mr. Robertson has dealt with apportioning the value of the refuse destructor is very pleasing. As an expert I have had to submit to many curious arguments as to why the value of the steam from the destructor is much less than the value of steam supplied by coal. I am quite aware there must be variations so long as there is an irregular supply of steam from the destructor; but this can be mitigated, if not entirely eliminated, and I would suggest the use of thermal storage as one means of levelling up the steam production. Mr. Robertson has mentioned the possibility of burning coal. This is perfectly feasible when suitable coal is fed at the right time, and it is surprising what efficiency can be obtained under these circumstances. Tests have been carried out recently by at least one eminent electrical engineer, and will shortly be made public showing what can be done in this way.

With regard to mechanical systems of handling the refuse, it will interest members to know that the latest system permits of selection of the material both in regard to quality and quantity. Arrangements are made by which refuse can be mixed when loads varying in character and composition are delivered, and arrangements are further made for

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Mr. Leask. the varying of the quantity to be charged into the furnace at one operation. This improved system has been adopted both in this country and on the Continent.

Mr. Watson. Mr. G. WATSON (*communicated*): Mr. Robertson has given a very interesting and strikingly impartial account of what is certainly the most important combined destructor and power station hitherto erected. As the joint patentee of the mechanical-charging system adopted at Greenock I am naturally prejudiced in its favour, but I am sure that Mr. Robertson has rather under than over-rated the advantages of the system, which was adopted by the Corporation of Greenock chiefly upon his recommendation. That the recommendation has been amply justified by experience appears clear from the facts and figures given in the paper. The variation of calorific value in the refuse at Greenock is exceptional, and its calorific value at the best is, I think, below the average. The fact therefore of an average net output of 67 units per ton over a whole year's working is remarkably good, and Mr. Robertson is quite justified in stating that it is the best result hitherto recorded for such a period. A result almost equally good has, however, been obtained at Batley, where with a "Horsfall" destructor in conjunction with the electricity works an average evaporation of over 1·25 lbs. of steam per lb. of refuse (this being the actual evaporation from water of ordinary temperature to steam at 180 lbs. per square inch) has been recorded over a whole year's working. The equivalent in electrical units cannot be stated, as there is no means at Batley of separating the actual units generated by the destructor from those generated by the coal-fired boilers. Mr. Robertson very properly discounts all results obtained on short trials. There has lately been a recrudescence of the practice of publishing high results obtained on trials lasting only 6 or 8 hours. On such a trial it is possible, by suitably manipulating the quantities of refuse in the furnaces at the beginning and end of the trial, and by forcing everything to its highest point of efficiency for a very short time, to obtain practically any result which may be desired. The absurdity of relying upon such figures is self-evident. They can give no guide whatever as to the actual results which may be obtained in ordinary working. I think it is incorrect to describe the cellular system as a system of "isolated cells." The cells are built in one or more compact blocks, and the principle of mutual assistance is developed to its highest point by means of the common combustion chamber, therefore the cells are in no sense isolated, although they are capable of being isolated at will by building a firebrick wall across the entrance of the combustion chamber. The comparative ease with which cells of this type can be clinkered as against those in which the gases from adjoining cells are all passing through the cell being operated upon is a great advantage for the cellular system, and one which becomes more apparent as the rate of combustion is increased. It should be noted that the rate of combustion per square foot regularly obtained at Greenock is about three times the normal figure on old-fashioned

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plants, and about double what has been done in modern high-pressure plants of hand-fired types. It would seem desirable for Mr. Robertson to give a further analysis of his labour costs, which appear high when compared with some published figures for hand-fired plants. They are only so in appearance, because Mr. Robertson has included the cost of cranemen, foremen, and weighmen, whereas in most published figures the labour cost is reckoned only for stokers. It is interesting to know that one craneman does all the work of lifting, storing, and charging the whole of the refuse in one shift, and two stokers in each shift do the whole of the work of tending the fires, clinkering, and removal of clinker. If the quantity of refuse admitted working the plant up to its full capacity all the time, the enormous saving over any system of hand-charging would be still more apparent. Mr. Watson

The use of chain grates referred to in the discussion is precluded by the nature of the refuse, which is much too poor a fuel to be satisfactorily worked by mechanical grates. This was thoroughly proved at Manchester and Huddersfield years ago. With regard to the utilisation of the heat of the clinker withdrawn from the furnace for heating the air, this is a scheme which has been put forward from several quarters for a good many years past, it having been, I believe, first put into practice by Messrs. Manlove, Alliott & Co. The special method adopted at Richmond, N.Y., is only possible in a "three-decker" plant, where the level permits a clinker floor to be placed below the firing floor, which is very rarely possible. The amount of heat to be obtained from the clinker in this way depends, of course, on how thoroughly it is burned before being withdrawn from the furnaces. If combustion is going on in the lower storey, of course more heat will be evolved than if the clinker is practically dead when drawn out. It is an unfortunate fact to which Mr. Robertson himself alludes that when steam-raising is the first consideration there is a temptation to withdraw the clinker before combustion is complete. It is worthy of remark that the destructor is credited with energy at 0·35d. per unit, which is the bare cost of coal saved, whereas the energy brought back from the electricity department is charged at 0·6d., or nearly double. I make no complaint of this whatever. I only draw attention to it, as this method of reckoning compares very favourably with figures which have been adopted elsewhere. The more Mr. Robertson's figures are studied the more it is apparent that they mark a new departure in the practice of the electrical engineer, and it is clear that the favourable results obtained, not only at Greenock, but at Liverpool and elsewhere, fully justify combined installations.

Mr. ASHTON BREMNER (*communicated*): There are some points in the paper on which I should like to make a few remarks: (1) Capital cost, (2) sanitary considerations, (3) labour costs, (4) repairs, and (5) revenue. I should also like to submit a comparison of the results at the Greenock destructor plant with those at one recently erected at Burslem by Messrs. Heenan and Froude, of Manchester. Mr. Bremner.

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Mr. Bremner.

The following are tabulated figures relating to both undertakings:—

	Greenock.	Burslem.
Capital cost of destructor, including one-half cost of site, one-half of chimney, buildings, furnaces, plant, etc.	£19,800	£4,525
Number and type of cells	Four cells, tub feed	Three cells, front feed
Capacity of plant per 24 hours	146·32 tons	39·26 tons
Tons of refuse destroyed per annum	16,995	7,800
Capital cost per ton burnt per 24 hours	£133	£112·5
TEST.		
Duration of test	8 hours	7¼ hours
Total grate area	80 sq. ft.	75 sq. ft.
Type of boiler	2 water-tube	1 water-tube
Total heating surface of boilers	4,140 sq. ft.	1,966 sq. ft.
Nature of refuse	Household and trade refuse	Household and trade refuse
Economiser...	Green's, 240 tubes	None
Total refuse burnt during test	32·25 tons	11·8625 tons
Capacity of plant per 24 hours	98·88 tons	39·26 tons
Total water evaporated during test	80,500 lbs.	49,990 lbs.
Evaporation per lb. of refuse burnt (actual) ...	1·11 lbs.	1·87 lbs.
Equivalent per lb. of refuse from and at 212° F. ...	1·41 lbs.	2·16 lbs.
Mean steam pressure ...	195 lbs. superheated to 564° F.	189·5 lbs., no superheat
Temperature of feed water	91·5° F.	45° F.
Maximum temperature of combustion chamber ...	—	2,300° F.
Minimum ditto	—	1,790° F.
Average ditto	—	2,032° F.
Percentage of clinker ...	—	26·5

Upon sanitary grounds, admitting for the moment that mechanical handling tends to greater cleanliness, which is questionable in view of the necessity of keeping all the boxes and spaces round them clean, it seems more sentimental than practical to object to the furnace men shovelling refuse into furnaces, when the same refuse has been collected only a short time previously by the ash men in the open street. The

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excessive capital cost cannot therefore be justified under this heading. Besides, it is generally agreed that the highest sanitation is that which benefits the greatest number, and this is more likely to be obtained by the uniformly high temperatures, and therefore more perfect combustion of the gases which is obtained with hand-fired destructors. The author admits the serious disadvantages of his method of charging, and, to my mind, the true sanitary efficiency of the plant is thereby impaired, half-cooked gases being necessarily emitted to the surrounding neighbourhood by the Greenock system. The temperature fluctuations on the chart (page 658) corroborate this, and it is not by any means certain that the chart records the extreme variations of temperature, as the readings were only taken at intervals. There is no saving under the heading of labour costs, which, during three years' working at Burslem, averaged 10d. per ton. The excessive capital costs cannot therefore be justified under this heading. Will the author say whether he has ever hand-fired his plant, and, if so, how this affected the thermal efficiency? Mr. Bremner.

The repairs during the first year at Greenock were £160, or 2¼d. per ton on 16,995 tons, whilst those at Burslem for last year (the third year of working) were £27, or 0·83d. per ton on 7,800 tons, so that the repairs bill at Greenock is heavy, and still one wonders if everything is included in the amount given, because the contractors usually keep the plant in order for at least six months after starting up. Had the makers no maintenance responsibility? Moreover, the Burslem plant is comparatively small, and has no standby unit, therefore higher costs might be expected. To enable a proper comparison to be made, it should be pointed out that the plant at Burslem consists of three compound non-condensing sets of 100-, 200-, and 350-k.w., capacity, therefore the steam consumption per unit could not possibly be so good as at Greenock, where much larger condensing sets are in use. In spite of this, and under actual working conditions, we average over 70 units per ton of refuse burnt. The price of coal at Burslem is comparatively low, and so the value of the units of electricity generated from destructor steam is relatively less than at Greenock, but, were my coal costs as high as the author's, so that I could afford to credit the destructor with 0·35d. per unit, the revenue from sale of steam would be about £800 per annum, and it should be remembered that this is with a lower load factor, and steam consumption, due to class of plant, almost twice that of the Greenock station. Reviewing these items, I am yet to be convinced that it is good engineering to adopt such an expensive plant. I have not had the advantage of examining the installation at Greenock, but, being familiar with the type of plant in use, I am of opinion that the forming of large openings in the crown of the arches must result in serious constructional weaknesses. I consider the high-water gauge and the consequent excessive consumption of power for forced draught unnecessary. At Burslem we find that a 2-in. water gauge is all that is required, with fires more than 18 in. thick, and that, instead of 8·5 per cent. of the units generated being used for blast

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Mr. Bremner.

purposes, as at Greenock, only from 4 to 5 per cent. is required. A higher pressure will cause "volcanoes" or holes in the fire, with impaired efficiency. We have a single land-type Babcock and Wilcox boiler, the gases being led three times through the tubes in the usual way, afterwards passing through a tubular regenerator before being led finally to the chimney stack. I have not found any difficulty due to the accumulation of dust on the heating surface, as is suggested by the author, catch-pits of ample depth being provided under each compartment of the boiler for the reception of dust.

I note the author's marine-type boilers have 2,070 sq. ft. heating surface each, two being in use with a destructor grate area of 80 sq. ft., whereas the Burslem plant has only one land-type boiler of 1,966 sq. ft. heating surface, and a grate area of 75 sq. ft. The temperature of the gases leaving the boiler at Burslem being about 450°, I do not think the use of an economiser is justified, though at Greenock the fact that the gases only once pass through the boiler makes it essential that an economiser be provided in this case, though, to my mind, the proper place to use the heat of the gases is in the boiler itself, and not in such an expensive and inefficient appendage as an economiser. The method of heating the air at the Greenock destructor is somewhat crude and inefficient, as obviously any heat that is imparted to the air must be extracted from the furnace itself, and I see that the author himself has noticed a further defect with the side-box heating arrangement—viz., that just at the time the air is required to be hottest, it is practically unheated. On the regenerative system of heating, as at Burslem, a temperature of 300° F. is attained, and, what is far more important, this heat is obtained from the waste gases on their way to the chimney stack.

The author suggests that the disadvantage of hand-firing is due to large inrushes of air above the grates when clinkering or charging. On the Burslem system such rushes are easily controlled by regulating the dampers, and a state of pressure equilibrium maintained between the outside and the inside of the furnace chambers. It should be remembered that, with forced draught, the function of the chimney is only to take away the products of combustion, and in substantiation of this I would refer to the very slight fluctuations in the temperature of the combustion chamber shown on the test quoted. In my opinion there is no doubt but that a properly designed combined electric light and destructor plant can be made a financial success and a benefit (other than sanitary) to the community by making the supply of electricity possible for power purposes at a very cheap rate.

Discussion at Dublin, May 13, 1909.

Mr. Pilditch.

Mr. G. F. Pilditch: I am not altogether in favour of combined schemes, for several reasons. First, there is the dust trouble, and in my experience no precautions will prevent dust from finding its way into the electricity works, and even if not sufficient to interfere with

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the working of the plant, it will give rise to a nuisance. Then again, in a plant used for steam raising, the refuse is generally burnt at a maximum rate when there is a demand for steam, and at a very slow rate, or perhaps not at all, during the remaining portion of the day, consequently, owing to the racking effect on the plant due to the great variations in temperature, the repairs bill will be very much higher, and the life of the plant shorter, than would be the case if it were used only for the purpose of destroying refuse, when burning would be continued at an even rate for the greater part of the twenty-four hours. And lastly, a refuse destructor can hardly be looked upon as a reliable steaming plant, owing to the very great variations in both the quality and quantity of the fuel. At the same time, I am quite prepared to admit that, given favourable conditions, some really good results can be obtained from a combined plant. Of course each particular case must be considered on its merits. We have been able to get some rather good results from our combined plant at Rathmines, because we are able to make use of all the generated steam whenever it is available, and to do without it at little inconvenience if, through shortage of refuse or from any other cause, the supply of steam be stopped. As regards the capabilities of this plant, the average of several tests taken under ordinary working conditions during the summer months shows an actual evaporation of 1·25 lbs. of water per lb. of refuse destroyed. The units generated were 35–40 per ton of refuse, but in addition to driving the electrical plant, the destructor boiler was, at the time of the tests, also supplying steam for working a clinker crusher and the fan for the forced draught. I am quite in agreement with the author as regards by-pass flues. Not only is the high temperature of the gases bad for the brickwork, but it causes the dampers to buckle, and consequently allows the gases to escape. Of course it is a great convenience to be able to shut off the boiler for cleaning and other purposes without interfering with the burning of the refuse, but from a steam-raising point of view it is far better to do without by-passes. With regard to the advisability of installing a large battery to level up the load on the destructor boilers, I quite agree with the author that in many cases it would not pay to do so, but here, again, each case must be considered on its merits. At Rathmines, for instance, owing to our street lighting load and other favourable conditions, it has well paid us to instal a large battery in order to utilise the steam from the destructor boilers. Referring to the question of charging the destructor cells, a good mechanical method is no doubt the right thing for large plants, but for plants dealing with anything under 35 tons a day, I think manual labour would work out cheaper. With regard to the position of boilers, I agree with the author that it is far better to place them beyond the combustion chamber than directly over it, as the chances of the gases passing away uncremated, or attacking the boiler tubes, are then reduced to a minimum. As regards forced draught, my experience has been that the most satisfactory results are obtained from a fan draught,

Mr. Pilditch.

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Mr. Pilditch.

the air being heated on its way to the ash-pits, and a small jet of steam supplied under the firebars to prevent them burning. We had considerable trouble at Rathmines when using fan draught alone, owing to the bars burning out, but since using the combined arrangement we have had no further trouble, and the clinker has been much improved. I might add that very little steam is required for the purpose.

As to the method of arriving at the value of the steam supplied by the destructor, at Rathmines, as at Greenock, owing to the electricity undertaking having been in operation for some time before the destructor, we are able to make a fairly close estimate of what the coal consumption would be if all the steam were still being obtained from coal-fired boilers, and the difference between the value of the coal actually used and the estimated value as above, is taken as the value of the steam supplied by the refuse destructor. Payments made on this basis appear to satisfy all concerned. I do not know of any satisfactory method of arriving at the value of steam supplied in those cases where the electricity undertaking and the refuse destructor have been started up together.

Mr. Price.

Mr. S. L. R. PRICE: With regard to the financial possibilities of a refuse destructor, I am of opinion that these undertakings are not sufficiently supported by the municipal authorities owning them. A great deal more use might, I think, be made of the clinker for making concrete blocks for pathways, etc., which would tend to make a success of a destructor scheme, and so assist the municipality. Fulham, I understand, does a good deal in this direction with very satisfactory results. With regard to the arrangement of cells, I am of opinion that the best type of destructor is that in which the cells are isolated from one another, discharging their burning gases into a common combustion chamber. This arrangement ensures a more even supply of heat to the boiler, and the steaming is consequently much steadier. The steadying effect also depends very much upon the brickwork of the combustion chamber being sufficiently massive, as the storing of heat in the brick walls materially reduces the fluctuating effect of charging the cells. A further advantage of arranging the cells in this way is that any cell can quite easily be cut out for repair without having to shut down the destructor. The gases seem to have a most detrimental effect upon dampers. This is most noticeable in the case of by-pass dampers, which necessarily have to work under most trying conditions, being subjected at times to the full action of the burning gases. We tried a water-cooled damper of the swivel type in connection with our Horsfall destructor for some time, but the joints were constantly giving trouble, and the arrangement eventually had to be abandoned. Sliding dampers gave trouble due to buckling and sticking in the slot, and in the end we had to resort to bricking up the by-pass with a dry wall, so arranged that it could easily be knocked down if desired, in a few minutes. As there are two Babcock boilers

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in connection with our destructor, variations of steaming can be obtained by shutting off one or the other, or allowing the gases to divide up and flow through both in parallel, by means of dampers beyond the boilers, where the gases are spent and harmless. When our destructor was first erected it was fitted simply with a steam-forced draught; but as I found that this was sometimes taking 20 per cent. of the steam generated at periods when we wanted the steam for electric generating purposes, I decided to put in a fan to work in combination with the steam blast, and this arrangement has proved most satisfactory, for at times when the steam is not required it can be used exclusively for blast purposes, and when the steam is required for electric generating purposes the fan is put on, just sufficient steam being used with it to warm and moisten the air, as the draught produced by the fan alone tends to the formation of an extremely hard clinker. Mr. Price

With regard to the payment by the electricity department for steam obtained, I am of opinion that as the departments are virtually worked as one, the destructor effects a considerable saving by the combination. In our particular case the necessity for a foreman is obviated, which effects a saving of at least £100 per annum. Then we pay all rates and taxes, and supply electricity for lighting and power free, and pay for any additional plant which was for our own benefit, such as an additional boiler when we decided that we could get more steam out of the refuse by its addition, and the fan, which was also for the purpose of enabling us to obtain more steam. When everything has been taken into account I estimate that we virtually save the destructor quite £200 per annum, which amply repays them for the steam supplied to us, adopting a similar basis of calculation to that set out by Mr. Robertson in his paper.

Mr. A. T. LAND: The principal object to be obtained in the destruction of refuse is to dispose of it in a sanitary manner with as little nuisance as possible, and any advantages to be derived from the heat evolved must be of secondary importance. In a properly designed plant it is quite possible to destroy the refuse in an unobjectionable manner, and yet obtain good results from a steam-generation point of view. At Rathmines, with a site hemmed in on three sides by residential property, there has never been a complaint of nuisance of any sort during the four years the plant has been in use, while the amount of steam generated by the refuse compares very favourably with results obtained in any other installation. The system employed is the back-hand shovel feed. My experience in a South of England town with the top-feed system, in which the refuse was dumped on the top of the furnaces, was that this system did not allow proper sanitary conditions, although, as regards steam raising, the results were remarkably good. This plant happened to be placed in a rather isolated position, otherwise a nuisance to outsiders would certainly have arisen. Mr. Land.

I do not agree with the author that the calorific value of refuse

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Mr. Land. in coal-mining districts is higher than in places where coal is dear. From cases that have come under my notice in both districts, I have found it quite the reverse. In North-country towns it is not usual for the refuse to contain unriddled ashes, or stuff that could be burnt with advantage in ordinary kitchen grates; but in the South, and particularly in Ireland, the inhabitants do not appear to be so careful, and the amount of useful fuel thrown into the dustbins is remarkable. I think the danger from dust finding its way into the engine-room is more apparent than real. It is difficult, in fact, almost impossible, to prevent it getting in, but I have never come across an instance where actual damage could be traced to its presence. With an engine-room 30 yards away from a clinker-yard, I have found the dust to be a nuisance but not dangerous. The tub-feed system in use at Greenock appears to possess the decided advantage of simplicity in handling the refuse, but from the temperature chart shown it does not appear to me that a more even temperature is attained than with hand-firing. I presume that the doors would have to be opened to "manage" the fires, and a skipload of haphazard stuff dropped *en masse* into the furnace would not give such good results as when hand-fed, in which case a certain amount of mixing good and bad is possible. Cases of fires with good combustion on the top, and cold on the bars would be liable to occur frequently with the tub-feed system, whereas with hand-firing they rarely occur.

The system installed by Messrs. Heenan and Froude at Richmond, U.S.A., with heating of the incoming air by hot clinkers, appear to me to introduce complications and disadvantages which would outweigh any benefit to be derived. The parallel arches in the same firm's destructors do, I think, ensure a thorough mixing of the gases and good combustion. A test of flue gases taken at Rathmines over a period of 8 hours gave an average of CO_2 13·9 per cent., O 5·7, and CO *nil*. I am not surprised to learn that the mixing of coal with refuse was not a success. The presence of unconsumed carbon in almost all refuse clinker had already led me to believe that full value would not be obtained from coal mixed with refuse. The destructor and electricity works should be treated financially as entirely different concerns, and advantages derived by one department from the other should be paid for and treated on business lines.

Mr. Tomlinson. Mr. T. TOMLINSON: Ten years ago, when this subject attracted public notice, very great claims were being made for the possibilities of refuse destruction in connection with electric lighting, and I was engaged by the *Electrical Review* to examine these claims, which I did in a series of articles, afterwards reprinted in Mr. Jones's work "Refuse Destructors." The general conclusion arrived at was that these claims were absurd, and that the sound policy was to develop the destructor as a destructor and not as a boiler furnace, and that, under this indispensable condition of development, the steam-raising power of destructors was of quite negligible value in electric lighting unless under very exceptional circumstances. I think this criticism has been

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fully justified by practice and results during the intervening years.

Mr. HOSGOOD: Mr. Robertson is right in emphasising the importance of keeping the sanitary aspect of the destructor in the first place. There is much room for improvement in the usual methods of collecting the refuse. The average householder's refuse bucket is by no means a sanitary article, and will often be found coated with a quarter of an inch of sludge, composed of fine ash and moisture, which the perfunctory tap against the dustman's cart fails to dislodge. The act of emptying the bucket into the cart is accompanied by a cloud of dust. Carts, although they may be of a covered pattern, have usually one or more of the doors left open while the cart is passing from house to house till its load is completed. In this dust-scattering, open condition it will meet the milk-cart, the bread-van, and other subjects for contamination. Articles of a useful nature—soiled magazines, bottles, and jars—run great risk of being pilfered on the journey to the destructor, thereby spreading dust and infection. Most of these dangers could be obviated if the householder were provided with a paper sack, roughly waterproofed, and capable of holding a few days supply. It could be tied, and carted unopened to the destructor, and would be thrown bodily on to the furnaces, thus simplifying the stoking. It would probably be a little more expensive than the bucket system, but certainly more sanitary. Mr. Hosgood.

The destructor roof has always seemed to me to be most insanitary, the tie-rods and girders forming splendid pockets for accumulating dust, which becomes impregnated with the emanations from the refuse lying below. Owing to its inaccessibility, this dust is necessarily left undisturbed for long periods, but in windy weather may be sprinkled down upon men and things below. Why should not the roof be ceiled and the corners rounded off as in hospitals, etc.? The refuse stokers have to work under trying conditions, and a reasonable amount of attention should be given to their comfort. In early days at Pembroke the men were occasionally laid up by chills caused by cold winds blowing in upon their backs from the open end of the building, while they were facing the hot furnaces. A pair of sliding doors which can be closed when weather conditions are adverse has proved an effective remedy.

Mr. ROBERTSON (*in reply*): I did not expect much support for my views from central station engineers, and Mr. Lackie has, I suppose, voiced the general opinion regarding combined stations. If the question is considered exclusively from the central station point of view, I can understand the engineer's desire to keep the destructor as far away as possible; but there is a wider interest to be considered, and I am convinced that from the ratepayer's point of view there is a very strong case for the combination, even in Glasgow. As to the waste that would be incurred through erecting six or seven small stations at suitable collection centres, I cannot see why the position of Glasgow should be any worse than that of Liverpool. Mr. Robertson.

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Mr. Robertson.

In that city there are now, I believe, six destructors situated at points round the city, which are equally suitable and convenient as tramway feeding-points and collecting centres. The generating conditions are certainly inefficient, as the engines run non-condensing, but notwithstanding the fact that 50 lbs. of destructor steam are consumed for each kilowatt-hour generated, no less than one-third of the total output of the Liverpool undertaking in 1907 was obtained from these small stations. Under the same generating conditions as obtain in Greenock or Glasgow, 18 million units might have been generated, or two-thirds of the total output. It has also been said that while combined stations may be suitable for small towns, they are impracticable in cities like Glasgow, and that although Greenock generates one-third of its total output from refuse steam, Glasgow could not have obtained more than one-tenth. Now I find that the Glasgow undertaking last year generated 32 million units, while Greenock generated 3¼ million units. On the basis of population, this works out respectively at 43 units and 45 units per capita. Assuming the amount of refuse to be proportional to population, there is therefore no reason why Glasgow should not generate from destructor steam at least one-third of its present output or even improve on the Liverpool results, which have been partly obtained from an old type of destructor with inefficient generating plant.

Every one admits it is essential, for sanitary reasons, to destroy the refuse by fire, especially in those towns which are so situated that suitable tipping places are not available, and it surely follows that any steam which is available from its destruction should be usefully employed. There may be cases where baths and wash-houses can utilise all the steam available; but these are the exception, and it is nothing less than criminal, I think, for electrical engineers to condemn the combination simply because the destructor is an unpleasant neighbour to have alongside a central station.

Regarding the use of chain-grate furnaces I believe that attempts have been made to burn refuse in this way, but the great variation in the nature of the material dealt with is the chief objection. A further difficulty is the closing in of the ash-pit to enable forced draught to be employed.

Mr. Newington inquired as to the cost of tipping, prior to the destructor being installed. The cost of disposal at a tip about 2½ miles from the centre of the town was 1s. 3½d. per ton, and the net cost of disposal now, including all charges, is 1s. 8¾d. per ton, a difference of 5¼d. per ton. Against this it is found that a considerable saving is effected through the centralisation of the cartage system, and that the Cleansing Department is now able to exercise a more efficient control over cartage operations.

Mr. Evans is sceptical about the calorific value of refuse, and appears to think that it consists only of old cans and rotten vegetables. This is by no means the case, and tests have shown that ordinary town's refuse has an average value of one-seventh to one-sixth the value of coal

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Mr. Robertson.

The diagram in the paper referred to by Mr. Willis falls to zero in July because of the annual holiday, which lasts for a week, when this station is entirely shut down and no steam used. Over the whole month of July it will be seen that the results show 26 units per ton.

I agree with Mr. Willis that there might be some benefit by using induced draught, and while hot air under pressure would still be necessary for combustion, it might be possible to regulate the draught at the chimney base by the employment of variable speed fans.

Communicated: I congratulate Mr. Bowden on the conditions which permit him to utilise a continuous supply of steam at the rate of 10,000 lbs. per hour for 24 hours per day. His results, when these come to hand, should be encouraging to the advocates of combined installations. My statement as to ashpit refuse giving the best results he thinks inconsistent with the fact that fresh coal when mixed with refuse does not burn satisfactorily. The true explanation is, I think, that a destructor is designed for the burning of materials which contain on the average not more than one-fifth of the amount of carbon present in coal, and that the rate of burning—assuming the correct proportion of air to give efficient combustion in each case—must therefore be vastly different. If all refuse consisted of half-burned coal from ashpits in working-class districts the difficulty would certainly be less, but in that case destructor design would be modified to suit the conditions. The "managing" of the fires consists in regulating the air pressure for each charge to give the best results, and the stirring and mixing of the refuse to ensure uniform combustion. Small oval doors, 6 in. by 4 in., are provided for this purpose in the large clinkering door to reduce the cooling effect.

I am glad that Mr. Bowden considers our figure of 1s. 8¾d. per ton to be an exceedingly low one, but I disagree entirely with his deduction that this has been brought about at the expense of the electricity consumers. The figure of 0·35d. per unit takes into account the whole of the circumstances, including the saving in capital cost of site and buildings. The destructor has been debited with the capital cost of feed pumps as well as the steam and feed piping required to deliver steam to the main steam range; the water evaporated in the destructor boilers is charged to destructor account, also a fair proportion of the wages and salaries expended in combined supervision. Under these circumstances the figure of 0·35d. per unit is not, I consider, too high. Mr. Bowden falls into an error in assuming the distribution efficiency at Greenock to be only 80 per cent., as at Poplar. The actual figure is 93 per cent., and the fuel costs for last year amount to 0·30d. per unit sold. I do not agree that the price paid for steam should be fixed irrespective of fluctuations in the price of coal. Here, I think, Mr. Bowden is inconsistent, as he also states that the price paid should be "not more than would be entailed by the use of coal." Surely the only fair method is to base the price paid for steam on the average rate paid for coal throughout the year.

Mr. Bowden has evidently overlooked the reason given in the paper

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Mr. Robertson.

for adopting a coal consumption basis to arrive at the value of destructor steam when he states I have not taken all standby losses into account. My position is that under this system the whole of the standby losses *arising from the combination* are debited against the destructor. This is emphatically the only correct method. But in face of his assertion that the destructor should carry all standby losses, Mr. Bowden is surely not serious in proposing that steam should be paid for on the basis of feed-water registration. Under this method the whole of the boiler-house losses—including condensation in steam pipes, blowing down of boilers, leaky steam traps and joints, to say nothing of steam blown off at safety valves at meal hours and at other times when it cannot be utilised—will be entirely borne by the electricity department. I can quite understand that on this basis of charging—which is still more objectionable when the two undertakings are under separate management—the amount paid for steam must make allowance for many different factors, and the price per unit under similar conditions should certainly be less than the figure paid at Greenock.

I have had no experience of a meter for registering the consumption of live steam, but I agree that such an instrument would be of much service. As all the current-using plant is required for working the destructor—except the clinker-crushing mill—the suggestion to charge a lower rate for a non-peak load is hardly practicable. The rate charged for energy supplied to the destructor is the rate which would be charged to any other consumer with a similar load factor.

Mr. Leask agrees with the general principles laid down in my paper, but takes exception to my criticism of hand firing. He emphasises my recognition of the disadvantages of the tub-feed system, and attributes the good results at Greenock exclusively to the economy of the generating plant. I have tried to steer clear of the controversy between the makers of hand-fired and mechanically-fed destructors, but as Mr. Leask has raised this issue, I have no hesitation in stating that there appears to be very little difference in steam-raising results between the two systems, while the sanitary advantages of the tub-feed system are so pronounced as to outweigh its admitted defects. The Greenock Committee visited many hand-fired installations before coming to a decision, and were unanimous in their finding that even if the steam-raising superiority of hand-fired installations was admitted, the objections to storing and handling such materials would prohibit the erection of this type of destructor on the site which had been provisionally selected near the centre of the town.

I must emphatically repudiate Mr. Leask's suggestion that the operation of a tub-feed system means the dissemination of objectionable gases from the destructor chimney. The destructor at Greenock has been working for 18 months without the slightest trouble or complaint of any kind; while, on the other hand, I know of several hand-fired plants which have given trouble from this cause. This is specially noticeable in "common grate" furnaces after the grate next to the combustion chamber has been charged. It will be admitted by all

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destructor engineers that thoroughness of cremation does not depend so much on the method of feeding the cells as on the amount of heat which can be stored in the brickwork of the furnaces and combustion chamber. Unless this brickwork is capable of storing sufficient heat to overcome the reduction of temperature which takes place in the newly charged cell, green gases will escape into the chimney with either system, and more so in "common grate" hand-fired furnaces, as the amount of brickwork in the furnace itself is less than in isolated cells. The slower process of hand firing as compared with "tub feed" leads to a further cooling down of furnace and combustion chamber. Mr. Robertson.

In the Greenock installation the combustion chambers are unusually large, and while a drop of temperature takes place after charging, there is sufficient heat at all times to prevent objectionable gases passing into the main flue. As two stokers and one craneman represent the whole of the labour employed in the destructor house on each shift, there is also a distinct saving in labour, and the work is comparatively easy as compared with hand-fed systems. In a similar hand-fired installation I have calculated that the work of shovelling 60 to 70 tons of refuse per day would call for at least four stokers per shift at a higher rate of pay instead of two, against which there would only be the saving of the wages of one craneman.

Mr. Leask and Mr. Newington are right in doubting that one craneman works for 18 hours at a stretch. One craneman is employed on each shift of 9 hours. Mr. Leask speaks of refuse from an agricultural district as giving 2½ lbs. water evaporation in winter and 1½ lbs. in summer, and truly describes this as an "astonishing result." I must confess that I am sometimes sceptical as to whether these astonishing results obtained from short evaporation tests do not harm destructor makers more than the criticism of central station engineers. Consider the question for a moment. One lb. of good coal, containing 5 per cent. moisture, will evaporate about 7 lbs. of water from and at 212° F. Average town's refuse contains about 30 per cent. moisture, and at least 15 to 20 per cent. of incombustible material. When due allowance is made for these deductions, an evaporation of 2½ lbs. of water per pound of refuse means that the remainder has a calorific value only 10 per cent. less than the value of good coal. Engineers who run destructor plants know how much value to attach to "tests" of this kind, but unfortunately these figures generally fall into the hands of municipal rulers who, while not possessing the experience to discriminate, have nevertheless to take the responsibility of expending large sums of public money in destructor plants, and much of the failure and disappointment of the past can be traced to exaggerated ideas based on so-called test figures.

Mr. Watson points out what I omitted to mention, that the rate of combustion per square foot of furnace grate at Greenock is extremely high. The figure is practically 1 ton per hour per grate of 25 sq. ft. In order to compare the result of a test with the normal rate of burning, I have taken the figures for the last six months, and find the average

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Mr. Robertson.

rate of burning to be 16·2 cwt. per hour. With regard to labour costs, it is only fair to explain that the figure of 1s. 1¼d. per ton includes not only stokers' and cranemen's, but gatemen's, wheelers', and chargemen's wages, also a proportion of charge engineers' wages from the electricity department, the latter being debited against the destructor as a return for supervision in the boiler house. Wages in the destructor proper—viz., stokers and cranemen—work out at less than 7d. per ton.

Mr. Watson is in error in stating that the figure of 0·35d. per unit for steam represents the bare cost of coal saved. The cost of coal per unit on the basis stated in the paper comes out at 0·24d. per unit, the remaining 0·11d. per unit representing the saving to the electricity department in capital charges and labour costs.

Mr. Ashton Bremner forwards a communication which has already appeared in the technical press, and submits an alleged comparison of the results at the Greenock destructor with those obtained from the installation at Burslem, provided by another manufacturer. Most of the figures are based on a misapprehension, inasmuch as it is assumed throughout that the destructor at Greenock consists of only four cells, while, as a matter of fact, the installation comprises six cells and three boilers, with clinker treatment plant. The Burslem plant appears to consist of one hand-fired unit without any standby, and minus an economiser. Such an installation is hardly comparable with the Greenock installation, even if it were shown—which it is not—how much has been paid respectively for site and buildings, and whether the Burslem installation has also paid for feed pumps, piping, etc. The water evaporation results in the Burslem test are of the kind referred to in my reply to Mr. Leask.

The cost for labour at Burslem is also "astonishing," as it appears Mr. Bremner is able to run his destructor and supply steam—presumably with regularity—at a total labour cost of £375 per annum. He ignores my explanation that the repairs bill during the first year's working at Greenock is really a charge for certain additions which have been made to the destructor and charged to revenue account, and in repeating an old-time fallacy about the structural weakness of top-fed cells, implies that the repairs bill has been due to this cause. In order to prevent mistakes, I may state that the brickwork of the Greenock furnaces during the first 12 months' operation, has cost absolutely nothing for repairs.

The remainder of Mr. Bremner's criticism is certainly a good advertisement for the type of destructor plant manufactured by the firm whose name he mentions, but has, I think, been anticipated in the paper itself.

I note that Mr. Pilditch experiences considerable trouble at Rathmines with fan draught owing to the bars burning out, but we have had no trouble whatever from this cause at Greenock, although I have heard of similar experiences with low-pressure furnaces. I note also that at Rathmines, as at Greenock, the value of steam is determined on

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Mr. Robertson.

an actual coal basis, and I agree that it may be difficult to find a satisfactory method of charging where the electricity works and the refuse destructor are started up together. I agree with Mr. Pilditch that for small installations it may be desirable for reasons of economy to adopt hand firing.

In reply to Mr. Land and others, it should be mentioned that the temperature chart shown in the paper is not taken on a test run but on an ordinary day's burning in October. Better charts have been obtained in midwinter, and I can easily understand that with careful hand firing on a *test* run a much straighter line might be easily obtained.

I agree with Mr. Hosgood in emphasising the sanitary aspect of the destructor. The importance of this point can hardly be overrated, and the gain of a few pounds per annum for steam supplied should certainly not outweigh the possible dangers to public health through the adoption of an insanitary system.

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THE DESIGN OF SMALL DIRECT-CURRENT MACHINES.

By B. E. STOTT and J. HARGROVE, Students.

(*Abstract of Paper read before the* STUDENTS' SECTION *in Manchester, March* 2, 1909.)

SECTION I.—THE SELECTION OF MATERIALS AND FACTORS DETERMINING THEIR UTILISATION.

Yoke.—We have the choice of the following materials for the construction of the yoke, each of which has its advantages and disadvantages:—

1. Cast iron.
2. Cast steel.
3. Malleable iron.
4. Wrought iron.

Whichever we choose, the cost of the yoke comes out about the same, the specific cost of the above materials varying practically as the permeability for the densities at which they may be economically used, having due regard to the weight of field copper which may be used to produce a design satisfactory from the point of view of cost, and also the volume of material required varying almost inversely as the permeability.

By employing cast iron we obtain a heavy and somewhat cumbersome design of yoke, which makes the machine weighty and large, not only by reason of the volume of material necessary, but by the enclosing of the machine by the yoke and consequently the more conservative rating which must be adopted.

On the other hand, a very strong and mechanical job can be made of the machine; clean and flawless castings with short delivery can easily be obtained—a point of the utmost importance; it also enables a small stock of castings to be carried.

Going to the other extreme, we may use cast steel, which gives a light open machine as near perfection as possible, but we have to be prepared to carry a large stock of castings to compensate for bad delivery—three weeks at the earliest—and irregular castings through warping or blow holes.

In between the materials already mentioned we have malleable iron and wrought iron. The former is not largely used, but it is very

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useful where a fairly light and small machine is required for early delivery, but there is considerable risk in using it on account of its variable magnetic properties, which depend entirely on the annealing process.

The latter is only used in special cases and for very small machines, when the yokes can be made out of bar metal on the anvil. It is very useful in the form of stampings for high-speed small machines such as are used for driving drills and emery wheels; where few slots are used the speed is high and the losses in the pole-face and poles themselves are consequently liable to be extremely large.

In general, from the technical and labour point of view, it is desirable to use steel, for it must be remembered that there are smaller surfaces to be machined and no poles to be fixed, as these are almost invariably cast with the yoke.

But on the practical side delivery, freedom from vexatious delays, and less wear and tear of tools all point in favour of the use of cast iron.

Magnet Cores.—These may be made of any of the following materials:—

1. Cast steel.
2. Mild steel.
3. Wrought iron.
4. Malleable iron.

1. Cast-steel poles cast with the yoke are very often employed where a cast-steel yoke is used, but in other cases it is hardly worth while going to the trouble of a special round casting when mild steel in the rod can so easily be obtained.

2. Mild steel is the material most often used. It can be easily obtained in suitable form, and can be cast into the yoke.

3. Wrought iron may be employed in the form of stampings, but this necessitates the use of a rectangular pole, which is not the most economical section to use as regards economy of field copper, besides much extra labour is involved in fitting them together and fixing.

4. In cases where malleable iron yokes are used it is found to be profitable to have the poles cast along with the yokes, and a pole-shoe fitted or not as the design and rating demands.

Pole-shoes.—For machines under ¼ H.P. no shoes are necessary; above this value and up to 1 H.P. the shoes must be either fitted, if the pole is part of, or cast in the yoke, and may be of fairly thick stampings (20 per inch) or of poor quality cast iron, or cast with the pole.

Above these values it is best to use shoes made of stampings, as it gives better control over the gap flux; of course, cast-iron shoes may be, and are used, but there is a great danger of excessive heating with the growing use of fewer but larger slots.

Commutators.—These are a frequent source of trouble in small machines, owing to the careless way in which they are put together; too much attention cannot be paid to the pressing and assembling of

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small commutators, as the reputation and behaviour of the whole machine depends upon this troublesome but necessary part.

Brush-gear.—No definite rules can be laid down as to which type of brush-holder to use, *i.e.*, the rigid brush type or the loose brush-box type, except in the case of reversible motors, where the latter is *sine quâ non.*

The former type gives very little trouble at moderate speeds, but is liable to chatter and chipping of the brush at high speeds.

The latter, however, operates satisfactorily at all reasonable speeds, it is not necessary to reverse the brush arms with reversal of the motor, and the holder being fixed can be made much more rigid than with the first type. It has this disadvantage, however, that the brush is liable to stick through dirt getting in the box; but this defect to a great extent can be avoided by coring or slotting out the corners of the brush box.

When the fact that the latter type is necessary for reversible motors is taken in conjunction with the advantages already mentioned, it will be seen that the gear which gives least trouble in fixing and arrangement is the loose brush type, and, in fact, many Continental and a number of English firms now adopt this as their standard practice.

Armatures.—Armatures for all sizes are now invariably built up of wrought-iron or steel stampings of the very best class of metal obtainable as regards magnetic qualities. In order to prevent loss by eddy currents it is necessary to insulate them from one another, and this is especially important in small armatures, as the frequency of magnetic reversal is generally large. For this purpose it is quite sufficient to rely on rust that may form on them, or upon a thin coating of insulating varnish placed on one side.

The construction is as simple as possible, and it is not advisable to use ventilating ducts with armatures of less than 6 in. diameter; it is much better to keep the losses down by keeping the magnetic density low than by pushing it unduly high, as is necessary in order to obtain air channels of sufficient size to be of any practical value.

It is possible to former wind all armatures of 3 in. diameter and upwards by properly proportioning the slots and keeping them as few as possible. This gives a much better balanced armature, and prevents trouble due to heating of the armature-end connections, since it admits of their better arrangement and ventilation, and is also much more convenient in case repair is necessary at any time.

The iron losses in the armature can be very much reduced by using special brands of magnetic alloy—*e.g.*, stalloy—and the output and efficiency of a given armature slightly increased.

Section II.—Data for Design.

Densities to be Used.—The following densities are intended as a guide to help in the correct proportioning of the magnetic circuit, and also in the suppression of sparking in the case of the air-gap. The

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densities in the magnetic circuit are very important, a large proportion of the total field ampere-turns being accounted for by the iron circuit and a relatively small portion by the air-gap when compared to larger sizes. In fact, quite usual ratios are—

$$\frac{\text{total ampere-turns on field}}{\text{ampere-turns on gap}} = 1{\cdot}7 \text{ to } 1{\cdot}5,$$

and these values may be safely taken in the estimation of the total field ampere-turns required if no magnetisation curve is available, as in the case of a first design. The most careful estimation of the magnetic circuit by the usual curves of permeability, etc., are almost useless on account of the variables encountered in the magnetic circuit itself.

The values below vary slightly with the relative prices of copper and iron, but so little that the variation can be ignored :—

	Material.	Lines per Square Inch.
Yoke	Cast iron	29,000–35,000
	Cast steel	89,000–90,000
	Malleable iron ...	60,000–70,000
	Wrought iron... ...	80,000–90,000
Poles	Mild steel	90,000–100,000
	Cast steel	90,000–100,000
	Wrought iron (S) ...	80,000–95,000
	Malleable iron ...	70,000–80,000
Armature...	Wrought iron... ...	50,000–70,000
Armature teeth	Wrought iron... ...	120,000–140,000 (corrected)

Gap.—In the air-gap it is advisable to keep the densities fairly low, especially in the smaller sizes, where difficulty is often experienced in finding the room for the field copper.

The values usual are given in form of a curve in Fig. 2, and these will give an economical distribution of iron and copper in normal cases.

In calculating these values the pole-face value of the area of the gap has been taken.

Leakage Factor.—This is much larger than is generally supposed, and varies from 1·4 or even 1·5 in the smallest sizes (60–100 watts) to 1·25 to 1·2 in the larger (5 k.w.); in fact, solely in order to keep the leakage down it is necessary in the smallest sizes to reduce the ratio of pole-arc/pole-pitch to 0·6, or even 0·55, in order to obtain an economical pole size, and consequently field coil.

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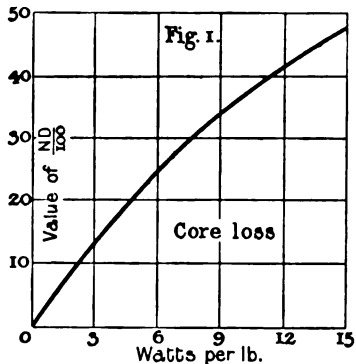
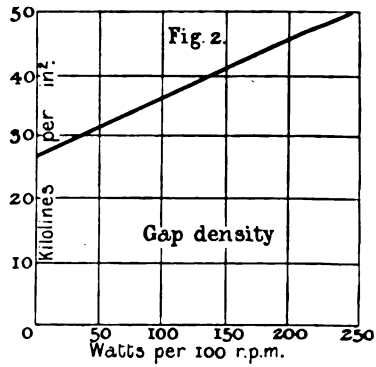
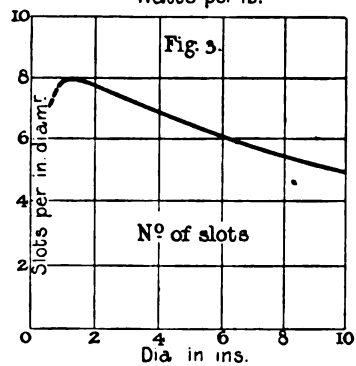
By careful design, by placing the field coil as near the armature as possible, by making the pole-shoe thin, the leakage can be considerably reduced, especially if a bent coil is used, as in Fig. 4, this enabling the







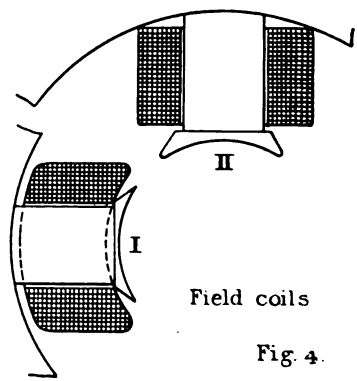


Fig. 4.

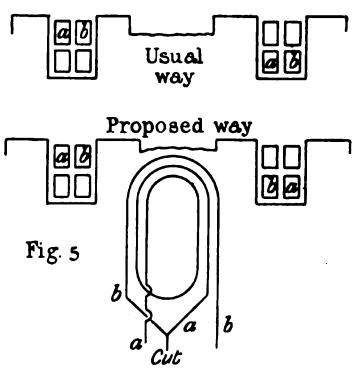


Fig. 5

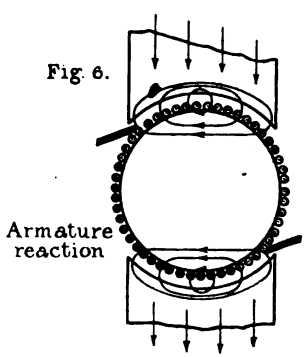


Fig. 6.

magnetic circuit to be much more effectively surrounded, besides enabling the radial length of the pole, and consequently the overall diameter of the yoke, to be made smaller.

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Armature.—The above must be chosen as low as possible in order to allow of former winding the armature, and also to reduce the labour cost in winding. The number of slots, however, depends to a large extent on the number of commutator sections which it is possible to use, but this can be got over by winding the coils as shown in Fig. 5. No difficulty is experienced by changing the position of the coils in the slots. The only difficulty with this method is when a dummy coil has to be employed for special cases, when sparking sometimes occurs.

The number of slots per inch diameter used is very variable, but a rough idea may be obtained from Fig. 3, where the number of slots per inch diameter is plotted against diameter of stamping.

The slot dimensions themselves should never exceed a ratio of 3 : 1 or be less than 1·5 : 1 except in the very smallest sizes, where a ratio of 1 : 1 has sometimes to be used; this should be avoided as far as possible.

The number of commutator segments is limited by the voltage per segment which may be allowed, and the largest safe value is about 30 in bipolar machines and about 20 in 4-pole, when wound for high voltage; a more normal value is from 10–15, which values will always give good results.

The commutator segments should be kept as few as possible on account of the cost and difficulty of manufacture of a commutator with a large number of thin segments.

Space Factor.—The space factor of small slots is very low, and on Fig. 7 are given the maximum and minimum values of the space factor for various-sized machines.

The values given are for round wires, double cotton-covered taped coils, and press-pahn or mica lining.

The space factor is slightly increased by using the method of winding already described.

The great difference in the space factors for high and low voltages for any given size shows the necessity for the liberal design of the field circuit and field coils so that the speed may not be unduly raised, or the temperature rise increased to make up for the decrease in space factor on high voltage. It is better to do this than lengthen the machine, as especially in the smallest sizes the voltage most often required is below 220, and only occasionally higher.

Field-coil Heating.—The data published for the determination of the temperature rise of field coils are very limited, and no rational method of correlating the results obtained on various sizes of coils under different conditions has yet been devised. In small machines the coils are more enveloped by the end frame, and thus approximate more in their behaviour to those in totally enclosed machines than in the larger sizes.

We give below a few figures, which may be taken as fairly safe guides for a first design, the conditions in each case being stated.

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The temperature rise is estimated by the watts per square inch of external cylindrical surface of the coil for 75° F. rise on the outside surface of the coil.

	Size.	Type.	Number of Poles.	Radiating Surface.	Watts per Square Inch.
	Kilowatt.			Square Inches.	
1	1	Open	2	145·0	1·50
2	1½	Open	2	110·0	1·36
3	0·75	Open / Protected	2	69·0	0·94
4	0·35	Open / Protected	2	47·5	1·05
5	5 H.P.	Open / Protected	4	100·0	1·30

As a safe guide the following values may be taken :—

1. For open-type machines at speeds between 1,000 and 1,800 revs. per minute, 1·25 watts per square inch.
2. For open-protected-type machines between 1,000 and 1,800 revs. per min., 1 watt per square inch.
3. For semi-enclosed machines with single gauze coverings, 0·85 watt per square inch.

The above values are based on a large number of experimental results, and will give a temperature rise of within 10 per cent. of 75° and the stated rise.

The whole of the above values are for coils with a ratio of layers to turns per layer of not less than 1 : 2 and not more than 1 : 0·75 (which are the outside limits for normal machines), and insulated with tape and presspahn, with no formers ; the latter being very seldom used on machines of the outputs under consideration.

Armature Heating.—The armature heating is determined by three main factors :—

1. The C^2R loss in the windings.
2. The iron losses in the core.
3. The peripheral velocity of the armature surface.

1. The C^2R loss in the armature depends solely on the length of winding used, the nature of winding, and the current in each section of the armature, and is quite definite and easy of calculation.

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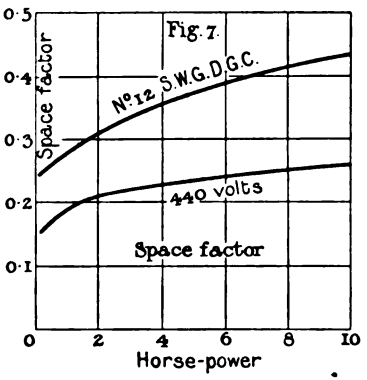
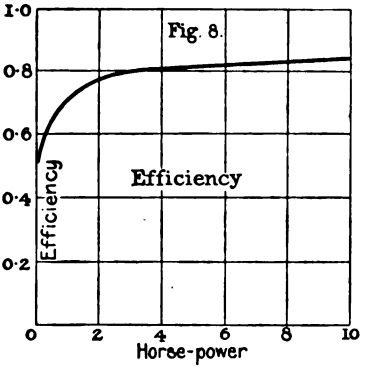
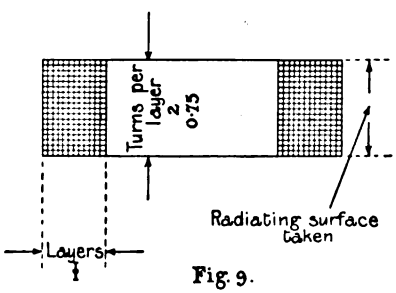
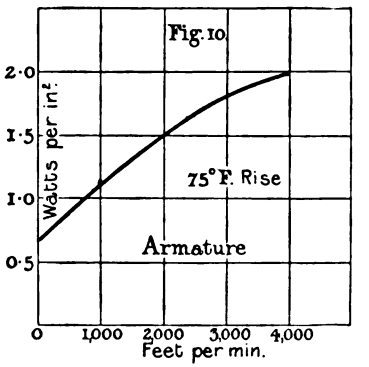
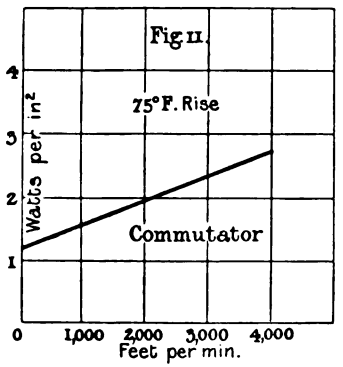
2. The second item is much more difficult to obtain accurately, and the error in estimation may be often more than 25 per cent., depending on how much filing has been necessary in the slots,

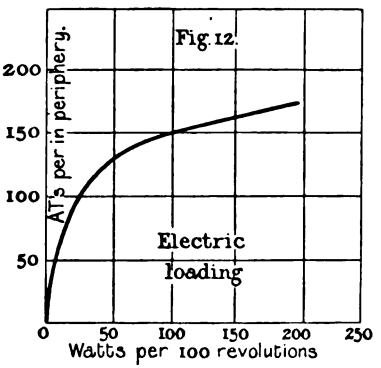












and also on how carefully the stampings have been assembled, to say nothing of the variation of quality of the iron often encountered.

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In Fig. 1 values are given, taken from a large number of machines plotted by the method adopted by Mr. Hobart, *i.e.*—

$$\frac{N\,D}{100} \text{ against watts per pound of flux-carrying,}$$

where—

N = magnetic cycles per second.
D = density in core in kilo lines per square inch of section.

Temperature Rise.—We are now in a position to determine the temperature rise. This may be estimated by means of the curve given in Fig. 10.

This curve gives the number of watts per square inch of radiating surface that can be allowed in order that the temperature rise may not exceed 75° F.

For rises above or below this figure the values may be interpolated, the watts per square inch allowable varying directly as the temperature rise within the limits required in actual practice.

Many methods of determining the radiating surface which should be taken have been proposed, but for small sizes the only one which gives consistent results is the one in this paper.

The radiating surface is taken to be the circumference × the gross length of windings, *i.e.*, it is the cylindrical surface of the armature and end connections.

No allowance is made for the pulley end or the commutator risers or lugs.

Commutator Heating.—This is estimated in the same way as the armature, and the necessary curve is given in Fig. 11, although the determination is not so accurate on account of the difficulty of determining the losses with any great degree of accuracy.

Brushes.—For voltages of 50 and above carbon brushes should always be used, and it is not advisable or necessary to employ any of the patent composition brushes which give more trouble than they are worth.

The brush pressure should not be less than 20 oz. or greater than 25 oz. per square inch. The maximum current density should never exceed 40 amperes per square inch, or trouble will be experienced by heating of the brushes on overload.

The voltage drop at the brushes may always be taken as 2, and brushes should never be used without copper pigtails, or pitting of the brush will surely take place where the finger engages the top of the brush.

A good value for the coefficient of friction may be taken as 0·3.

Heating of Totally Enclosed Machines.—In the case of totally enclosed machines the temperature rise is determined by the watts radiated per square inch of external radiating surface.

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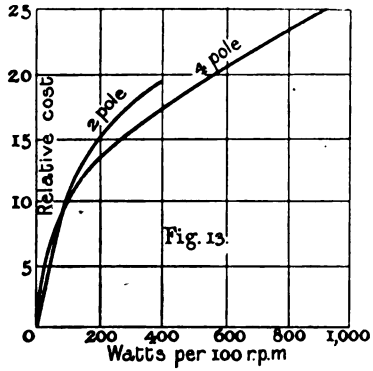
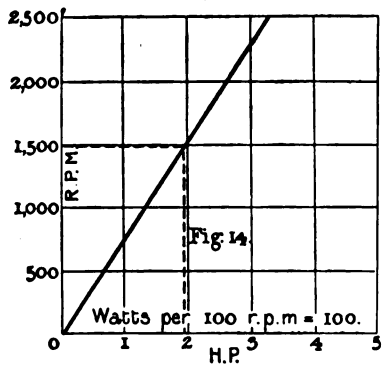
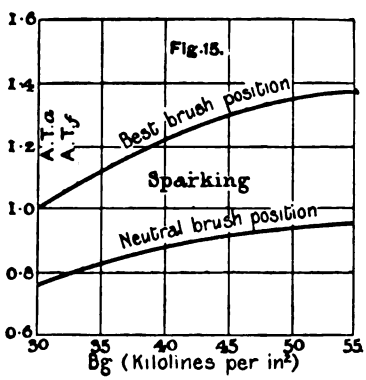
For a rise of 80° F. the values vary between 0·25 and 0·3 watts per square inch.







The total outside surface of the machine being taken, *i.e.*, the outside cylindrical surface of the yoke and commutator covers plus the surface of the ends.

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Section III.—Determination of Size.

It was first shown by Esson, and rationally by S. P. Thompson, that a definite relation exists between the dimensions, the output factor, and the watts per revolution of a dynamo electric machine.

These relations were shown very clearly by Messrs. J. C. Macfarlane and H. Burge in their paper before the London Section on September 11, 1908, and they give the following final equation :—

$$B \times q = K \times \frac{\text{watts}}{\text{revs. per minute}} \div d^2l.$$

From this we see that the product of the electric (q) and magnetic loading (B) is proportional to the watts per revolution per d^2l, and on Fig. 16 are given the relations existing between these quantities plotted in quadrants for ready reference.

The values given refer to machines having a ratio of pole-arc to pole-pitch of 0·7 and square pole-faces. For machines having different dimensions the values must be corrected as below :—

Actual output—

$$= \text{output for square pole-face} \times \frac{\text{actual revs. per minute}}{100} \times \frac{\text{nett actual core length}}{\text{core length for square poles}} \times \frac{\text{ratio actual pole-arc to pole-pitch}}{0{\cdot}7}.$$

From the four quadrants we can obtain for any machine—

1. Output for a given speed.
2. Preliminary dimensions for any output within the scope of curves.
3. The various design constants of any machine, whether already made or projected.

In Fig. 12 the values of the electric loading in ampere-turns per inch of armature circumference are also given, plotted on a base of output/speed for square pole-face machines.

In the above curves the output values are given as watts per 100 revolutions for convenience of plotting.

Selection of Number of Poles.—From the quadrant curves we can determine for any given output the armature dimensions of a machine for any number of poles, but not the correct number of poles to use. In Fig. 13 curves are given connecting the total works cost of bipolar and 4-pole machines with the watts per 100 revolutions.

It will be seen that these two curves cut at a value of 100 for the watts per revolution, *i.e.*, below a value of 100 the bipolar machine is cheapest; and above, the 4-pole machine. The exact meaning of this statement is made clear by Fig. 14, which gives the horse-power and speed corresponding to a watts per 100 revolutions of one hundred.

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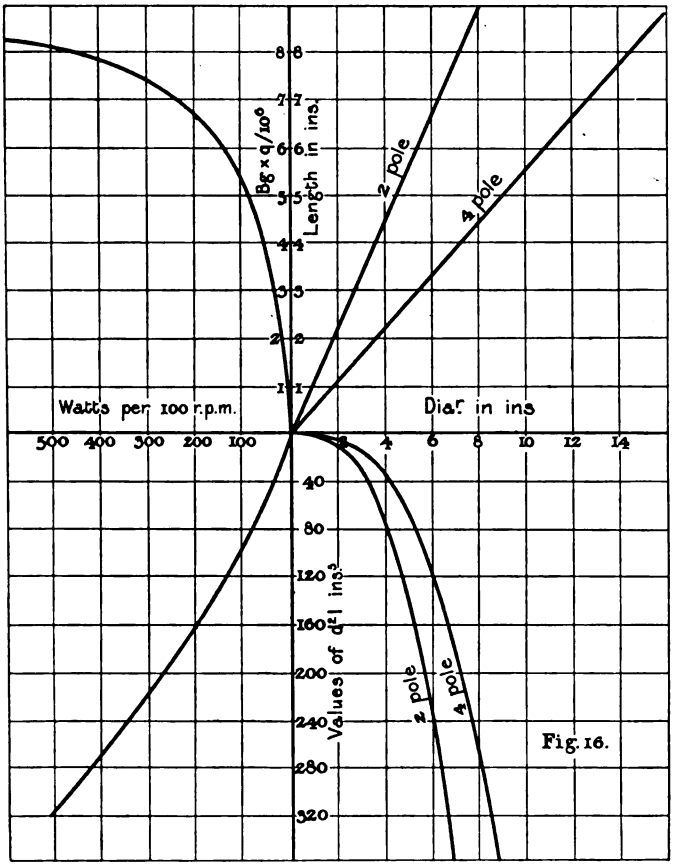
Very conveniently the rule may be given as follows :—

The costs of a 4-pole and a 2-pole design are equal when the revs. per minute equal the watts output of the machine.

The above value can only be taken as approximate on account of the variation of labour charges, cost of power, etc., in different districts.



Output Quadrants.

Commutation.—Sparking is produced by the current which flows in the coils short-circuited by the brushes, and is due to the self-induction of the coils themselves. The voltage of self-induction (or reactance voltage) producing this current is opposed by the voltage induced in the coil by virture of its rotation in the field produced by the field ampere-turns. If the difference between the two is excessive we get sparking.

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To obtain the least possible difference between the reactance voltage and the rotational voltage we have to keep the flux density under the pole-tip, where the coil undergoing commutation is situated as high as possible, and limit the number of turns in the slots.

The weakening of the field is due solely to the cross-magnetising effect of the armature ampere-turns lying under the poles, as shown in Fig. 6.

The ampere-turns of cross magnetisation are :—

$$X_c = \frac{Z \times B \times i_a}{360},$$

where—

Z = number of conductors on armature.
B = pole-angle.
i_a = current flowing in each section of armature.

The principal reluctance in the path of the cross ampere-turns is that due to the air-gap, and, neglecting the reluctance of the iron, we have—

$$B_c = \frac{0{\cdot}4\,\pi \times X_c}{l_g},$$

where—

B_c = density under tips due to cross ampere-turns.
l_g = double air-gap length.

Combining this with the equation—

$$B_g = \frac{0{\cdot}4\,\pi \times X_g}{l_g},$$

i.e., the equation for the main field, we have for the actual strength of the commutating field—

$$B = B_g - B_c = \frac{0{\cdot}4\,\pi (X_g - X_c)}{l_g},$$

i.e., the difference between X_g and X_c must not be less than a certain value ; to obtain this value is difficult, except empirically, but what can easily be done is to express X_c in terms of X_g.

X_g is practically constant, and, therefore, we can guarantee that the difference between X_g and X_c is sufficient, provided the ratio $\frac{X_c}{X_g}$ does not exceed a certain value.

As shown already, X_c is a constant proportion of the armature total ampere-turns, and the gap ampere-turns are practically a constant proportion of the total field ampere, so that we may write instead of—

$$\frac{X_c}{X_g},$$

$$\frac{\text{total armature ampere-turns}}{\text{total field ampere-turns}}, \text{ or } \frac{X_a}{X_f}.$$

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In Fig. 15 are given ratios at which sparking commences for various field strengths obtained from actual tests.

It is interesting to follow the variation of sparking voltage with voltage of machine, which may be done as follows :—

Let the voltage of the machine be V.
The current per section in armature i_a.
The turns short-circuited t.
For a given frame and speed the reactance voltage $\propto t^2 i_a$.
For a given frame and speed the rotational voltage $\propto t$.

But—

$$t \propto V,$$

and—

$$i_a \propto \frac{l}{V}..$$

Hence we may write—

$$\text{reactance } V \propto \frac{V^2 \times l}{V} \propto V,$$

$$\text{rotational } V \propto V.$$

Hence—

$$\text{sparking voltage} = K_1 V - K_2 V$$
$$i.e. = V(K_1 - K_2),$$

i.e., the tendency to spark varies directly as the voltage.

This is borne out by actual experience, for a machine has to be designed as regards sparking for the high voltage only, and should be better the more the voltage is lowered, but for the lower voltages the output can only be very slightly increased without increasing the length and the cost *pro rata*, since we are limited by heating, the slight increase in output being due to the better space factor obtainable.

It has already been shown that the sparking voltage is dependent on the ratio $\frac{A T_a}{A T_f}$, and provided the ratios above given are not exceeded at the highest working voltage the machine will not spark, and will not heat excessively provided the values for heating given in Fig. 10 are not exceeded.

The above method of evaluating the sparking constant of a machine has in its favour that it takes into consideration the density of the air-gap, which the reactance voltage method does not, and that it still prevents the armature strength from being too great.

It may be argued that this method does not look after the sparking for all voltages since it is a constant for any given design, but it is certain that if a machine is assigned a suitable value of $\frac{A T_a}{A T_f}$, it will not spark on the higher voltages, provided the value of the voltage per segment is not unusually high, since it only deals with the maximum permissible sparking voltage—*i.e.*, the difference between the reactance and rotational voltages—and not the reactance voltage only, which takes no account of the rotational voltage or the density under the pole-tips producing it.

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The calculations and tests are quite simple, and only involve the running of the machine at full field current and speed, and increasing the armature current until sparking occurs.

Considerations affecting the Design of a Machine.—The total works cost of a small machine consists largely of labour charges, and any economy in price should be made by reducing these and not by cutting down the machine to the very finest limits.

Reduction of Labour Charges.—These may be reduced only by making the machining as small as adequate with a sound mechanical job, and by using the cheapest possible labour in winding.

The machining and labour may be reduced by :—

1. Casting the poles in or on the yokes.
2. Making the end-plates solid with the yoke and boring the tunnel and end-plates at the same time.
3. Making the field coils simple, and former winding the armature coils on a winding machine so that boys or girls may do everything except actually place the coils on the machines.
4. Adopting the method of armature winding indicated earlier in the paper, and thus reducing the number of coils to be placed in position on the armature.
5. Using several commutators for the different voltages, and accommodating the number of segments to the voltage, thus reducing the expense entailed in building up and connecting down the commutator.
6. Putting through as many frames as possible at one time.

Reduction of Cost of Material.—The most economical machine to build is the one which has the shortest length of mean turn on the armature and *field*.

The design which fulfils these conditions is the one in which round steel poles are used and the pole-face is square.

There is no difficulty in using a round pole, since the flux per pole is determined by the radial depth of armature core that can be allowed. For bipolar and 4-pole machines the maximum flux can be easily carried by round poles without restricting the space for the field copper. If other pole-shapes are used the length of mean turn of the field is increased, and consequently the cost of winding and field copper.

The following example shows the necessity of reducing the field copper and its great influence in determining the cost of net effective material :—

Output 5 B.H.P. at 1,000 revs. per minute.

	£	s.	d.
Field copper	2	10	0
Armature copper	0	10	0
Yoke	2	0	0
Armature laminations	0	9	0

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From the above figures it is clear that the field-shape giving the shortest mean turn must be employed, and this shortest length of mean turn is obtained by use of the square pole-face. If we depart from the square pole-face, the pole-diameter becomes so large in comparison with the width or length of the pole-face that the space for the field copper is restricted and the leakage becomes serious, and we have to revert to the rectangular or elliptical pole.

The use of interpoles would reduce the actual weight of main field copper, but the extra cost of material and fitting involved more than discounts any reduction in the main field. The saving is further neutralised by the fact that in order to find room for the interpoles the field-pole has to be made rectangular, and the most economical pole section cannot be used.

It is very doubtful whether it ever pays to use interpoles on standard designs below 5 k.w., whatever the price of copper.

The authors tender their best thanks to the Crypto Electrical Company for their kindness in allowing data of their machines to be used in preparation of this paper, and also to Principal Reynolds, Professor Schwartz, and the Committee of the Manchester Technical School for permission to use their laboratories for some few special tests.

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NOTES ON THE ELIMINATION OF SPARKING.

By LAURENCE H. A. CARR, B.Sc.Tech., Student.

(*Abstract of Paper read before the* STUDENTS' SECTION *in Manchester, January* 19, 1909.)

The object of this paper is to describe some experiments made with a special twin brush to obtain an insight into the commutation problem, and its solution by the use of interpoles. The special twin or "pilot"

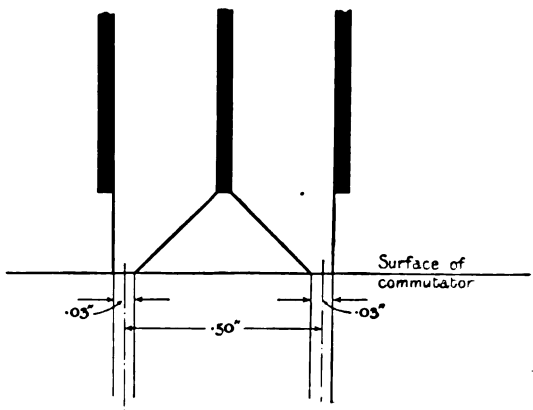

FIG. 1.—Pilot Brush.

brush used in these experiments really consists of two brushes mounted together but insulated from each other.

Fig. 1 shows the general arrangement of this brush, the two portions of it being made of carbon. The centre lines of the two portions were $\frac{1}{2}$ in. apart, and the thickness circumferentially was considered negligible (actually it was 0·03 in.) The axial length bearing on the commutator was $\frac{1}{4}$ in.

This was run on a (4-pole) commutator of $7\frac{1}{2}$ in. diameter, which gives a circumferential span of the brush of $15\frac{1}{2}°$ of polar arc. When the machine is being rotated with main brushes lifted, this pilot (which was made to fit into the standard box-type holder of the machine) will

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at any point, when connected to a voltmeter, give the volts generated by that particular $15\frac{1}{2}°$ of armature.

Also from this, if the speed and number of turns on the armature be known, the flux enclosed by this $15\frac{1}{2}°$ can be calculated, and if we assume uniformity of flux in the armature, B the flux density.

When comparing results of different armatures it would be necessary to calculate results right down to this fundamental B, but when comparing results on the same armature under similar conditions the volts read by the pilot may themselves be considered, as they are then proportional to the induction.

If we consider the flux around the neutral position, we see that by placing the pilot brush with its centre line coincident with the geometrical neutral (Fig. 2), whatever be the shape of the pole-tip fringe, so

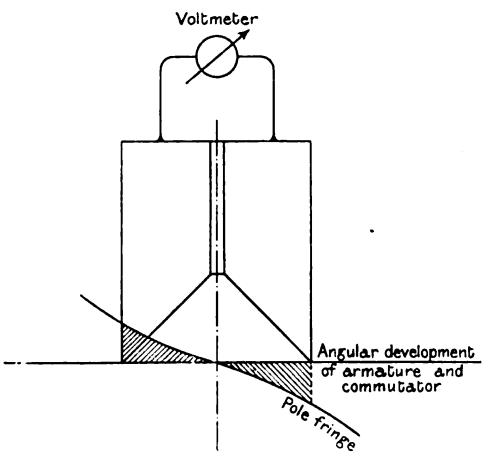

FIG. 2.—Pilot Brush in Neutral Position.

long as the machine is symmetrical the pilot will read no volts, for the volts generated by the turns passing between the two halves of the pilot will total zero, as the + and — flux areas are obviously equal.

If we consider the machine on load either as dynamo or motor, we have superposed on the field flux the flux produced by the armature. Since the two halves of the field flux counteract each other, the armature flux alone may be considered.

The volts induced by the armature conductors cutting the field induced by itself will vary as $\frac{N_1 - N_2}{t}$, $N_1 N_2$ being fluxes, t time of cutting; that is, the average rate of cutting lines of force by the segment of the armature embraced by the two halves of the pilot.

Care must be taken to give $N_1 N_2$ the correct signs relatively to the current.

If N be assumed proportional to C, the current in the armature, or

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in other words, the permeability of the path be assumed constant, it may be said—

$$V_1 \text{ varies as } \frac{N_1 - N_2}{l},$$

i.e., varies as $\frac{C}{l}$ where $V_1 =$ volts induced.

In addition to this purely electro-dynamic E.M.F. there is also to be added the E.M.F. of self-induction.

The self-induction volts vary as C the current, and also as the frequency; or, in other words, inversely as the time of reversal, hence V_2 varies as $\frac{C}{l}$, where $V_2 =$ self-induction volts.

Total volts—

$$V = V_1 + V_2, \textit{ i.e.}, \text{ varies as } \frac{C}{l},$$

that is, varies as current × speed.

The sum of these two voltages V is the voltage that was measured by the pilot brush.

Tests were run as follows, the results obtained being shown in Figs. 3 and 4.

The machine which was tested had an armature of 10 in. diameter, wound with 1,305 turns of 0·045 d.c.c. wire. The commutator was $7\frac{1}{2}$ in. diameter, and had 145 bars.

The machine had 4 poles, and the armature was connected 2 "circuit single."

Ratio of pole-arc to pole-pitch = 0·7.

The brushes used for the test need a little description. The pilot brush previously mentioned, with $\frac{1}{8}$ in. centres between the two halves, was bushed round with insulation (mica bound up with stamp edging), so as to fit a standard $\frac{3}{8}$-in. box-type holder. This holder was of the two-brush pattern, the pilot being put in one box, and the other was filled by a $\frac{3}{8}$-in. wide hard carbon brush which had previously been filed down $\frac{1}{16}$ in. on each bottom edge, so that these edges coincided with the centres of the pilot.

The other holder had standard brushes in it.

Connection was made to the pilot brushes as follows. These were made from a standard brush, the top of which was coppered. This copper was tinned and flexible leads were soldered on, and thus connection was made to a voltmeter.

The machine was driven round as an open-circuit separately excited dynamo, and the lead adjusted till the pilot read no volts, though the full armature volts registered 500. The field was then switched off and current supplied to the armature only from an external source, the machine being driven round by another motor.

Curve 3 shows a set of readings taken with a (main) current of 10 amperes and various speeds.

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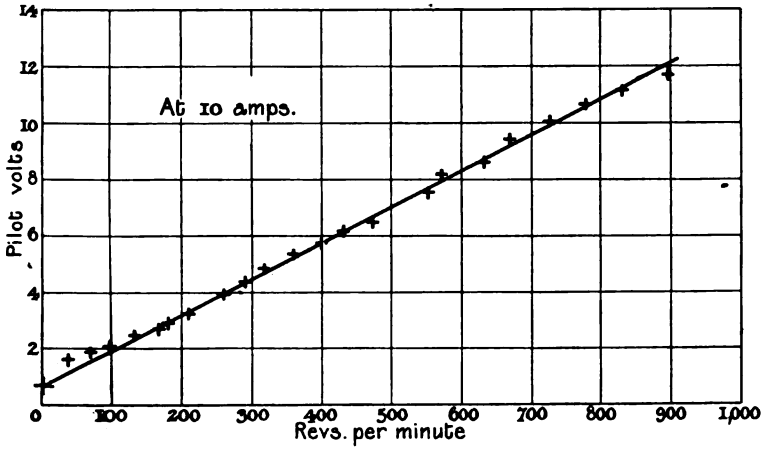

FIG. 3.

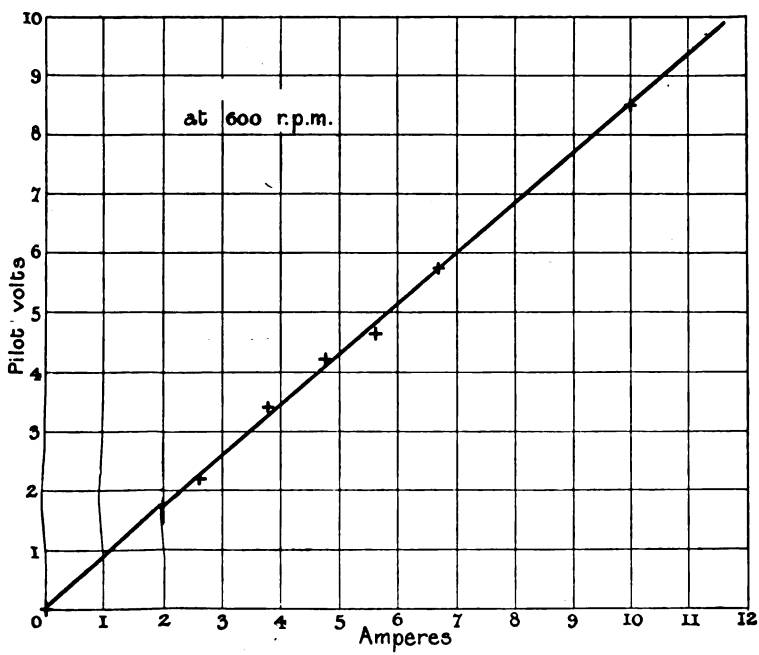

FIG. 4.

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Curve 4 shows a set of readings taken with a constant speed of 600 revs. per minute and varying armature current.

From the curves it will be seen that these sparking volts do actually vary with the speed and armature current.

It will be noticed that in Fig. 3 the curve does not pass through the origin, *i.e.*, with the armature stationary and current flowing through it there was a difference of potential read by the pilot. This was attributed to uneven bedding, and hence uneven distribution of the current under the brush.

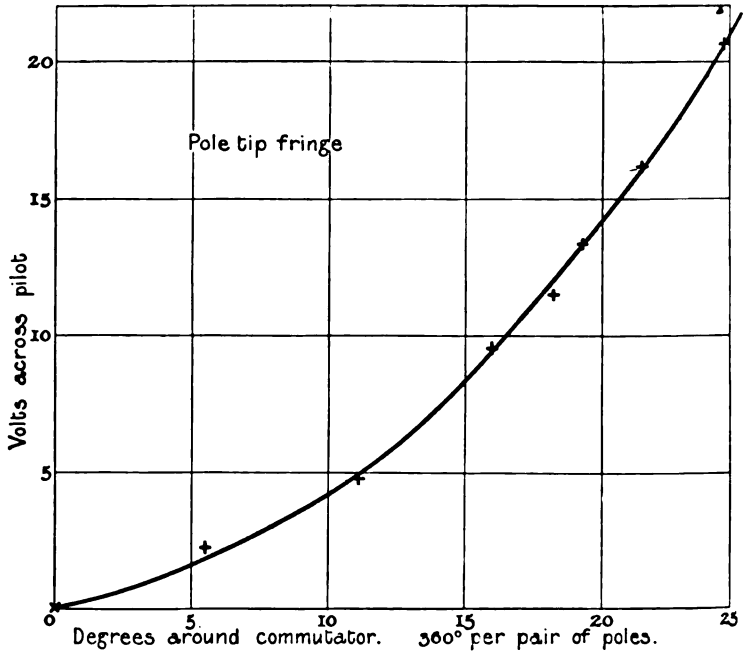

FIG. 5.

So far the case has only been considered where the brush has been placed in the geometrical neutral. If it is swung one way or the other there is an additional voltage induced in the short-circuited coil or coils due to the field flux that it is cutting. In the case of a motor, if we put the brushes backward this voltage induced opposes the self-induction and armature flux voltages and so aids commutation. If it exactly equals the other two voltages then there is no voltage to produce sparking, and hence commutation is perfect. I have run a curve to obtain the shape of this pole-tip fringe by running the machine open-circuited with full field and giving the pilot brush different angles of back lead, reading the volts across it.

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A pointer scale, etc., was rigged up for this test.

This test could not be run on the same machine as before (for commercial reasons), but has been corrected by a multiplying factor to reduce it to the same terms. A machine of identically the same dimensions was used, and the readings were corrected for—

1. Ratio of total field flux;
2. Ratio of armature turns;
3. Speed of the two machines;

being directly proportional to the product of the three.

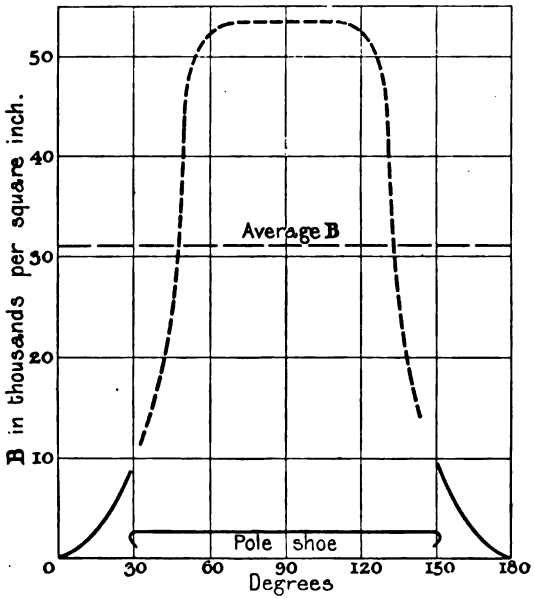

FIG. 6.

Fig. 5 gives the results as obtained, plotted on a curve.

Fig. 6 shows the same readings calculated as values of B so as to show the portion of the curve actually taken. The average induction in the armature under the pole-face is given, having been calculated, and from this the dotted line showing curve of B throughout the face has been drawn in. This curve is merely a guess, but indicates the portion of the total curve that has been explored.

Returning to Fig. 5, this gives some idea of the lead to be given to the machine for correct commutation at any load and speed. For instance, at 600 revs. per minute, which is the speed of the machine motoring at 500 volts with full field, with a load of 10 amperes, referring to Figs. 3 and 4 we find a voltage of 8·5 registered by the pilot.

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To get perfect commutation, from Fig. 5 we determine that the correct lead to induce these volts from the pole fringe is about 15° of polar arc.

It would, of course, be advisable, however, in actual practice not to give the machine this lead unless it were always running at full load, but rather it would be given the lead necessary to produce half these volts—*i.e.*, from the curve a lead of nearly 11°, so that from no load to full load the sparking volts would vary from + 4·75 (pole-tip fringe volts only) to + 4·75 − 8·5 = − 4·75. Shifting the lead would possibly alter the values obtained in the curves 5 and 6, but as long as the short-circuited coil is not right under the pole-tip itself the error will be slight.

In the case of a reversing motor, of course these remarks do not apply, as it is bound to run in the geometrical neutral.

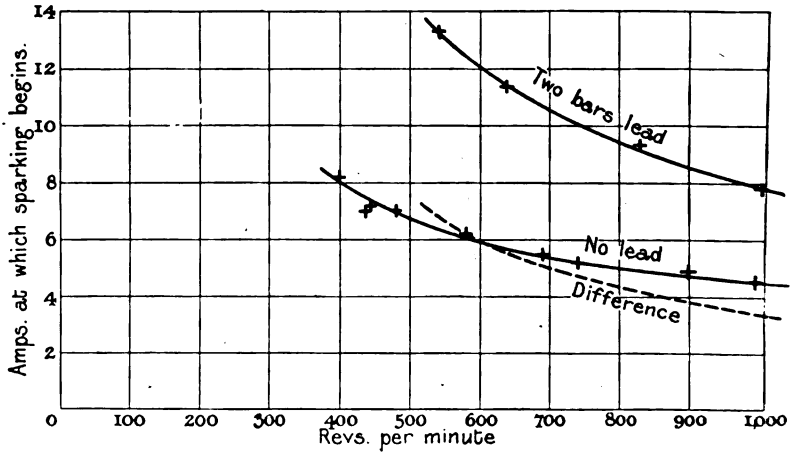

FIG. 7.

As an actual example of the advantage of giving a motor back lead, Fig. 7 shows graphically the result of an experiment made with a small motor. The machine was run as a motor on the geometrical neutral lead, and the speed gradually increased by weakening the field. Readings were taken at the load at which sparking commenced. This is rather hard to determine exactly; however, by gradually weakening the field (thus both speeding up the motor and also increasing the load) the points could be moderately well determined.

The curve also shows the results obtained when the machine was given a backward lead of two commutator bars.

When interpoles are fitted, to obtain the best results the machine must be run with geometrically neutral lead.

In theory the armature ampere-turns are neutralised by the interpole ampere-turns, and further, by adding more turns on the interpoles a reverse flux is set up across the short-circuited conductors, E.M.F.

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generated by which opposes the self-induction E.M.F. (just as the backward pole-fringe would if the machine were given a backward lead), and so gives perfect commutation. In actual practice the correct ratio of ampere-turns on interpoles and armature is, however, a matter to be determined, as the armature ampere-turns are wound on a cylinder, while the interpole ampere-turns are wound on salient poles which

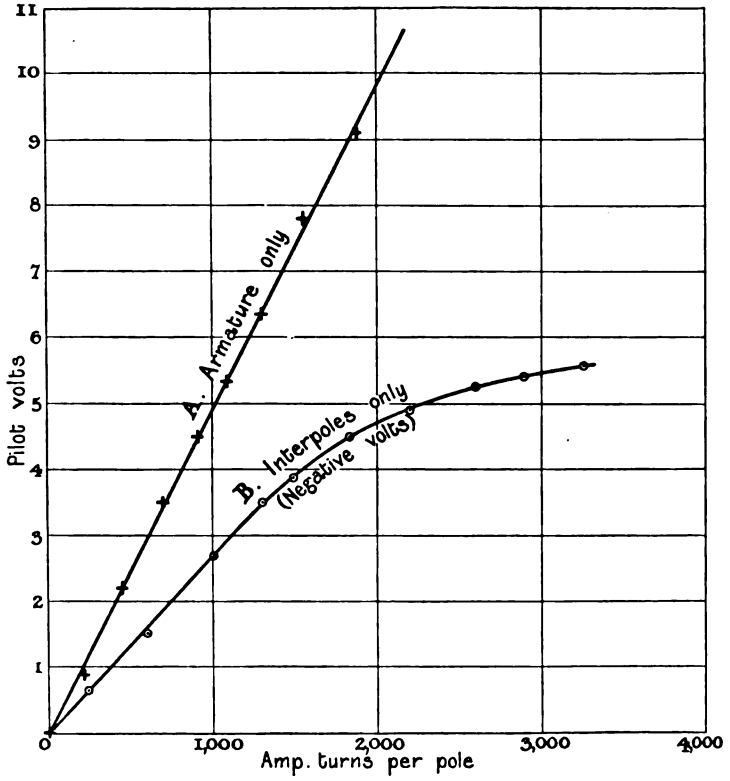

FIG. 8.

are small, and which may become saturated. There is also the leakage to be considered.

The tests to be described were run on a machine similar to those used in the previous tests except that it had a greater axial length. In this particular case the interpoles were not the full (axial) length of the armature but only 0·294 of its gross length. The interpoles spanned 0·094 of the pole-pitch. The test was run with the help of the pilot brush as before and the correct neutral position obtained. The armature was then rotated from an external source. The shunt field

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circuit was broken. The armature and the interpoles were connected to two independent sources of supply.

The volts across the pilot were then measured at constant speed under varying circumstances.

Fig. 8, curve A, shows results obtained with the armature excited but no field on the interpoles.

Curve B, no armature excitation, interpoles excited. This is obviously a magnetisation curve of the interpoles. It must be noted that these volts are opposite to those induced by the armature field.

In the figure they are plotted the same way for comparison. The great difference between the two curves at the lower end is due to the

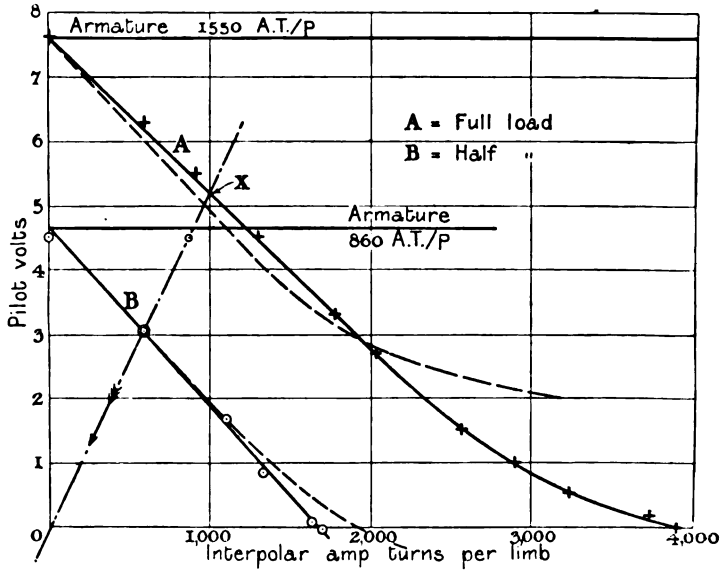

FIG. 9.

two facts : (1) That the armature ampere-turns are on the same core as the short-circuited (which is practically a search) coil, while the interpole turns are on another core, with an air-gap between, which means leakage, and also (2) that the self-induction volts in the short-circuited coil only exist in curve A. At the upper end curve B is obviously affected by the saturation of the interpole.

The effect was then tried of keeping a constant current on the armature and gradually increasing the interpole excitation.

Two curves were taken (Fig. 9, A and B), A with an armature current of 36 amperes, which we may call full load, the other, B, with a currrent of 20 amperes, or approximately half load.

It must be pointed out that the top point of curve B does not quite

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agree with the corresponding point on curve A in the last figure. This is probably due to the presence in the interpole of residual magetism.

In each case a chain curve is drawn in. This is the curve B of the last Fig. 8 plotted underneath the line representing the volts generated due to the armature action only. This shows that saturation of the interpole does not take place until a much higher magnetising force is applied to the interpoles, which is what would naturally be expected.

The right end of curve A is very similar to the curve due to interpole only with the zero shifted from the point (0, 7·65) to (1,000, 5·5). This is shown in Fig. 10, and seems to indicate that in this machine with an armature current flowing the flux through the interpole is zero

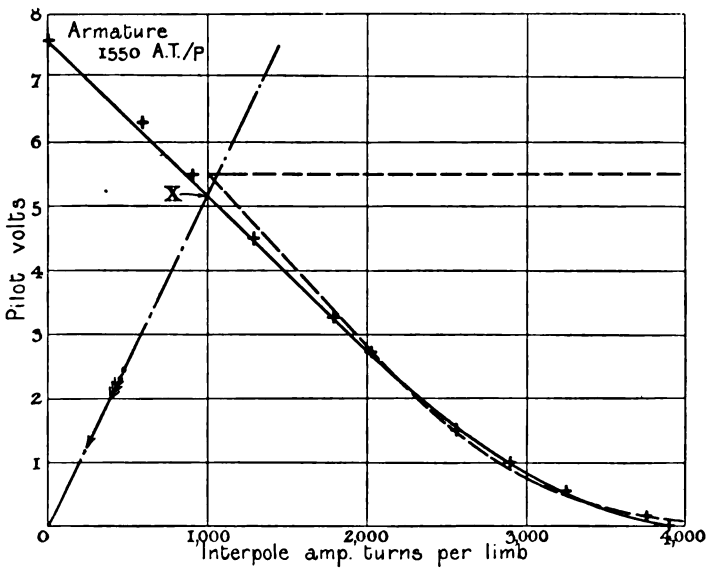

FIG. 10.

when its own turns are two-thirds those of the armature, and that this relation may be utilised to determine the saturation of an interpole under working conditions.

With regard to the interpolar turns required by this machine from the shapes of A and B, Fig. 9, it seems probable that to get intermediate curves the curve A should be slid down not vertically, but along the line O X.

In this case if we make the interpole-turns a certain number depending on the straight part of the curve, then the machine will be exactly compensated as long as the saturated part of the curve is below the ampere-turns axis; in this case about three-quarter load, but above this, there will still be a small sparking voltage to be absorbed by the brushes, which will increase as the machine is overloaded.

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In the machine under discussion, the straight-line part of the curve gives a ratio of almost exactly two, that is, interpole-turns should be equal to the armature-turns, the interpoles being all in series, and the armature having a 2-circuit winding.

Referring to B, Fig. 9, we should then have at half load 860 ampere-turns on the armature and 1,720 on the interpoles (per pole), giving a point almost on the zero line. Below this, and above it to about three-quarter load the same compensation would occur, but when full load is reached there are 1,550 ampere-turns on the armature and hence 3,100 on the interpoles, giving a sparking voltage of ¾ volt across the brush to be absorbed in the carbon, which is quite allowable. As the machine is overloaded this voltage will, of course, increase. It will also increase proportionately to the speed; but if the speed be raised in a 4 to 1 ratio, by shunt regulation, this sparking voltage across the brush would be raised to 3, which is also quite safe on a machine of this size. It must be emphasised that the strength of the shunt field is in this case quite immaterial, as it does not enter at all into the commutation problem.

As to the modification of the shape of this curve, it is obvious that widening the interpole circumferentially is of no use as long as the conductors simultaneously under short circuit are under the pole all the time they are shorted. This is a mechanical consideration depending on number of slots, pitch of windings, etc., and can readily be settled for any given machine.

Lengthening the interpoles axially, if they are not the full length of the armature, will increase the volts due to the interpole field, and hence bring the curve down more sharply, thus cutting the ampere-turn axis sooner, with a twofold effect—first, the maintaining of the full compensation up to a higher armature load, and secondly, reducing the number of turns on the interpole necessary to do it. From this point of view a full-length interpole is an advantage.

Consideration of the above results leads to the conclusion that far from being an additional complication, the interpole actually simplifies the theoretical considerations necessary to ensure good commutation, and that this is the ultimate solution of all sparking troubles.

The interpole should be of ample length axially, however, to avoid saturation and consequent sparking at slight overloads.

In conclusion, I must thank the Lancashire Dynamo and Motor Company, Ltd., for permission to carry out the above experiments on their test-bed.

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SINGLE-PHASE RAILWAYS.

By PERCY C. JONES, Student.

(*Abstract of Paper read before the* STUDENTS' SECTION *at Manchester, December* 8, 1908.)

In considering the advances made by various systems of electric traction as applied to railway working, the rapidly extending use of the single-phase type is very noticeable. It is perhaps advisable to mention here that the name of the system is generally taken from the type of motor used for propelling the train, and these types may be broadly classified under three headings :—

(*a*) Direct-current.
(*b*) Single-phase.
(*c*) Three-phase.

Each heading can, of course, be subdivided to designate the type more accurately, as, for instance, there are the high- and low-tension direct-current motors, single-phase series, and single-phase repulsion motors, and so forth.

The system on which the current is generated need not be that used on the train motors, as 3-phase generation, for instance, is applicable to all the three forms of motor when supplied to the train line through suitable converting apparatus.

In this paper it is proposed to describe some recent railway equipments on the single-phase system, and then, as it seems also necessary in order to properly realise the advantages and disadvantages of any particular system to consider the same points in competitive systems, a review will be made of the three.

The Midland Railway Company's Heysham, Morecambe, and Lancaster line is of particular interest as it is the first single-phase line to be put into operation in this country, and in view of the Manchester students' visit to this line the following particulars will not be out of place :—

Fig. 1 shows in plan the extent of the electrified lines, and also gives particulars of the gradients and curves. The line comprises the double roads between Heysham and Morecambe, Morecambe and Lancaster Green Ayre, and the single line from Lancaster Green Ayre to Lancaster Castle Station, the total length of single road being about 21 miles. The power station, which is situated at Heysham, is a gas-driven one working from two "Mond" producers, each of about

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750–1,000-H.P. capacity. This station originally provided only direct current for working cranes, capstans, lifts, and other machinery, together with the lighting of the harbour at Heysham. The engine-room originally contained three Westinghouse 250-H.P. 3-cylinder gas engines, each driving 150-k.w. 460-volt generators. For working the electric railway these sets have been supplemented by one 350-H.P. engine and

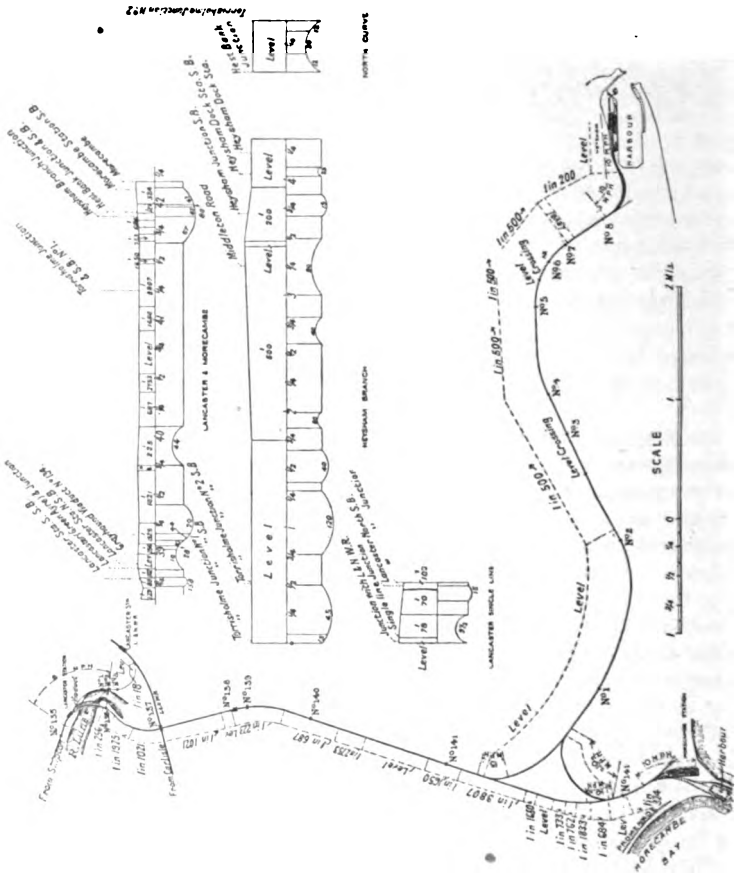

FIG. 1.—Plan and Diagram of Gradients—Lancaster, Morecambe, and Heysham Branch, Midland Railway.

a 235-k.w. 460-volt direct-current generator of the same Company's make. The station contains a battery and booster for taking care of the "peak" loads.

Single-phase current is obtained through two direct-current alternating-current motor-generators by the Electric Construction Company. The continuous capacity of each of these sets is 150–200 k.w. at 6,600 volt, 25 cycles; but as the load may vary from nothing to upwards of

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1,000 k.w. in very short periods, they are each capable of carrying an instantaneous overload of 900 k.w. The voltage regulation is well up to the requirements, and variations due to sudden change of load do not alter the line voltage of 6,600 volts by more than 300 volts either way.

The alternating-current side of each motor-generator is connected to the busbars by a hand-operated oil switch, and the current from the busbars passes through duplicate automatic circuit breakers and duplicate feeders to the overhead lines. The incoming wire from the rails is at earth potential, and no other feeders to remote parts of the line are used.

Considering now the overhead equipment, this is of the catenary type. The contact wire is of figure 8 section, and is run in lengths of from 800–1,000 yards. One end of each length is fixed through insulators to a terminal gantry, and the other end is attached through suitable pulleys, etc., to a weight of about 1,200 lbs. The wires are so arranged that the trains always travel from the fixed end to the weighted end, and the tendency of the bows is therefore always to straighten the contact wire. The suspension of the contact wire differs from that on other lines by a modification introduced by the Midland Railway Company. This consists in the provision of an auxiliary steel cable from which the contact wire is suspended by short loops about 4 in. long. The auxiliary wire is in turn suspended from two catenary cables. Fig. 2 shows the insulator used for supporting the catenary cables and also the loop for suspending the contact wire from the auxiliary cable. The contact wire is horizontally staggered on either side of the centre line of the coach in order to distribute the wear over a greater surface of the bow than would result if it were unstaggered. The stagger was first made equal to 2 ft. on either side of the centre, but it is now considered that a 1-ft. stagger is preferable. It may be mentioned here that in American practice a 9-in. stagger is found to be quite sufficient.

The track is bonded throughout its length on the outer rails with duplicate Forest City type bonds placed under the fish-plates, and at crossings and junctions all rails are bonded together. At Morecambe and Heysham the rails are earthed in the sea by duplicate copper earth-plates, and at Lancaster they are connected to the cast-iron columns of the bridge where they rest in the river-bed.

The rolling stock was built by the Railway Company and consists of three motor-cars and four trailer-cars. The electrical equipments of two of the motor-cars were supplied by Siemens Bros., and the remaining one by the Westinghouse Company.

All the motor-cars are of the open central corridor type having a total length of 60 ft. over the end panels and an extreme width of 9 ft. There are two bogies on each car having 8 ft. 6 in. wheel base and 3 ft. 7½ in. diameter wheels, this dimension being on the tread when new. There are two motors per car, and these are mounted on one truck. Broadly speaking the main difference between the two equipments lies in the control systems. On the Siemens cars the switches

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which make the connections for starting and reversing the motors, etc., are closed by single-phase magnets acting against springs, whereas the switches on the Westinghouse car are closed by compressed air also acting against a spring. On the Siemens equipments the motors are rated at 180 H.P. each, the full voltage being 340. They are of the series-compensated type with a special auxiliary commutating winding on the stator. There are 8 poles and 8 sets of brushes, and the motors

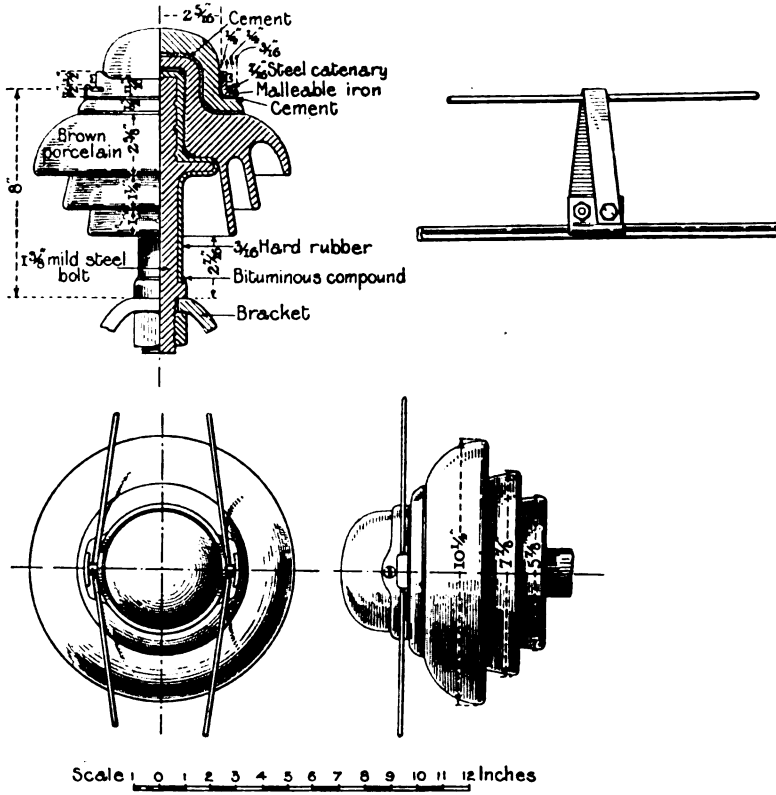

FIG. 2.—Line Insulator and Contact Wire Clip.

are arranged for forced ventilation. A diagram of connections also indicating all the apparatus on the Siemens car is shown in Fig. 3. From this it will be seen that the current path from the contact wire is down the two bows in parallel through the choking coil and main automatic switch to the main transformer high-tension winding through which the current will pass to ground. Separate low-tension windings are provided for the motors, and from these windings tappings are taken to the switches which vary the potential on the motors. The

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switches are controlled by a hand-operated master controller in the driver's cabin. This master controller only handles the 150-volt current for energising the switch magnet coils, which is a low pressure and has no connection with the main power or high-tension circuits. It will be seen that an auxiliary transformer provides the low-tension current for the magnet coils and also the pump motors and lighting circuit. The Westinghouse car is equipped with two motors, which are of the series-compensated type having 6 poles and 6 sets of brushes. The rating is 150 H.P., but as the forced ventilating method first introduced by the Westinghouse Company on the Metropolitan Railway is used they have a large overload capacity.

A simple diagram of the power circuit as arranged by this Company is shown in Fig. 4. It will be seen that there is a single main transformer winding, one end of which is earthed and the other end

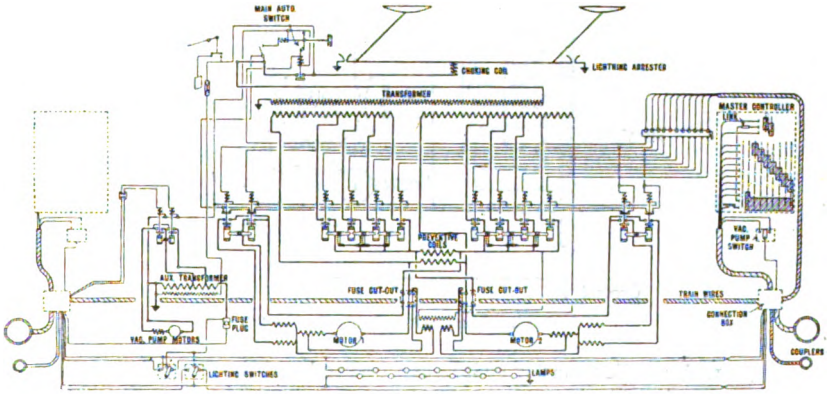

FIG. 3.—Diagram of Connections—Siemens' Control System.

connects with the 6,600-volt contact wire through the circuit breaker and trolley bow. The switch group, preventive coils, reversers, and motors are also indicated. On the first step switches 1, 9, 10, 11, and 12 are closed simultaneously, and 2, 3, and 4 automatically follow connecting the preventive coils to the low-voltage taps of the main transformer. This step applies the minimum pressure to the motor circuit. The second step causes switch 1 to open and 5 to close applying an increased pressure to the motors, and this is further increased on successive steps. The primary use of a preventive coil is to enable the voltage on the motors to be increased without either opening circuit on passing from one step to the next or momentarily short-circuiting a section of the transformer. By using three preventive coils as shown in the diagram, the path of the current to the motors is through four switches in parallel. This allows a smaller size of switch to be used than if one or two carried the whole current.

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The motors are reversed by a separate drum-type switch which changes over the field connections.

The individual switches of the switch group, main switch, and the reserve drum are all operated by compressed air acting on pistons in small cylinders which have valves controlled by alternating-current magnets, the circuits of which are excited in proper sequence by means of the master switch.

Electro-pneumatic control has several advantages over the all-electric system, amongst which may be mentioned—

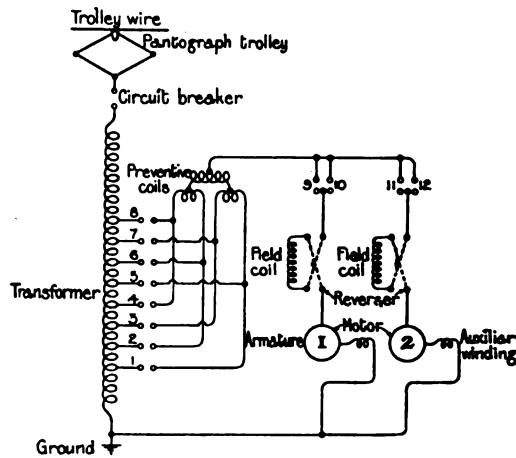

FIG. 4.—Diagram of Connections.

1. A smaller master switch can be used and the currents handled by this for the small valve magnets will be very much less than for those of the magnetically operated switches.
2. The switch group is lighter for a given capacity.
3. The use of air for closing the switches gives greater power and renders them independent of fluctuations of line voltage.
4. Less power is required for operation.

The provision of air-compressing apparatus will in some cases not be entirely on account of the control apparatus, as where air brakes are used the supply for these can be utilised.

The master switches on both makers' equipments are of the "dead man handle" type. The mechanism of these switches is so arranged that when applying power, if the driver releases the forward pressure necessary to move the handle, the main circuit will be automatically opened and the handle will have to be returned to the "off" position before power can be applied again to the motors.

The main transformers on both equipments are oil insulated. This is desirable on account of the high voltage and also to prevent the entry of moisture into the windings.

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On the Siemens car two bows are fitted for collecting the current, while in the Westinghouse car only one is used. The former are normally held down by a spring, and a vacuum cylinder provides the power for raising them up. The latter type are normally held up by a spring and lowered by air pressure to such a point that they are retained down by a catch. This catch can be released by air pressure from the compressor, or by means of a small hand pump. Hand pumps are provided on both equipments so that the bows can be raised when either vacuum or air pressure as respectively required are unavailable.

The cars just described are representative of the most recent practice in single-phase equipments suitable for operating as motor coaches.

On equipments of lower power if the multiple unit system of control is not required, hand-operated controllers may be used. An example of this type is furnished by the Thamshaven Railway in Norway, recently put in operation by the Westinghouse Company, the general particulars of which are as follows: The railway is of metre gauge with 20 miles of track. The contact line is fed from a sub-station at 6,600 volts, 25 periods. This sub-station receives 3-phase current at 15,000 volts, 50 periods, which is supplied from a water power station. The sub-station contains two 15,000/6,600 volts 3-phase oil-insulated transformers and two motor-generators of 250-k.v.a. continuous capacity. The motor is of the 3-phase induction type with slip rings, and is direct coupled to a single-phase revolving-field generator; an exciter is also on the same shaft. The contact line is on the single catenary principle, being suspended from insulators mounted on steel brackets of T section, which are attached to wooden poles.

Three electric locomotives have been provided for working goods and passenger trains, each weighs 20 tons and carries 4 motors on two bogies. Each motor is rated at 40 H.P. for 1 hour and is of the single-phase series-compensated type. The 4 motors are arranged in two groups with two in series in each group. A hand-operated controller at either end of the loco is used to connect the motors with the low-tension tappings off the transformer. There are five steps in which the voltage is proportionately increased when starting or for speed regulation from 240 to a maximum of 540 volts. Further particulars of the type of control system used can be found in Mr. H. W. Taylor's paper on "Single Phase Railway Working," published in the Institution *Journal* for 1906, vol. 37.

An example of the use of electric locomotives for tunnel work is found in the operation of the St. Clair tunnel, which connects Port Huron in U.S.A. with Sarnia in Canada. The actual length of the tunnel is 6,032 ft., the electrified approach on the American side being 6,098 ft., and on the Canadian side 7,218 ft. The total length of electrified line is therefore a little short of 3¾ miles. There is about 1 mile of 2 per cent. grade on either side leading from that portion of the tunnel which is directly beneath the river.

The power-station equipment is in duplicate, there being two

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1,250-k.w. 3-phase 25-cycle 3,300-volt turbo-generators, either of which is capable of dealing with the maximum demand on the station. Outside the power station is a vertical shaft which extends downwards to the tunnel. Through this shaft pass the line feeders which are directly connected to the contact line in the tunnel at this point, and no other feeders are used for supplying more remote parts of the line. Although the generators are wound for 3-phase, the locomotive load will leave one winding free, and it is interesting to note that this method of generation is frequently adopted as it provides a spare winding which can be utilised if anything goes wrong with one of the other two. In the tunnel a modified form of catenary construction is used, and the steel messenger cables which support the contact line are as close as 3 in. to the iron tunnel shell. This seems a short distance considering the voltage is 3,300 between the bare cables and the shell, but no trouble has occurred on this account. The locomotives each weigh 66 tons, and are generally used in pairs; each pair is capable of drawing a 1,000-ton train up the tunnel approaches which requires a 50,000-lb. draw-bar pull. The full speed of the locomotive is about 11 miles per hour on the grade. Each locomotive has 3 pairs of 62-in. diameter driving wheels, each pair being driven by a 250-H.P. single-phase motor through a gear and pinion. The motors are of the 10-pole compensated type, and are designed to operate at a normal voltage of 235 with a frequency of 25 cycles. The three motors are connected in parallel, and by means of cut-out switches any one or two can be isolated without preventing the operation of those remaining in circuit. A blower is provided to ventilate the motors and also the main transformer. The continuous capacity of the motors with forced ventilation is 750 amperes at 235 volts. This rating would permit two locomotives to pull a 2,500-ton train at a constant speed of 15½ miles per hour for any length of time on a straight level track. The control gear is of the electro-pneumatic type operated by means of a small master switch. It is interesting to note that the valve magnets which govern the admission of air to the switch piston cylinders are operated by direct current. This is obtained from a 20-volt storage battery, of which two are provided, so that one is in use while the other is charged by means of a small motor-generator set. The master controllers operate the switches so that by connecting the motors to different tappings on the transformer 17 running and 3 switching notches are provided, these latter being used for running the locomotive slowly without any load. Two or more locomotives can be operated from one master controller when their control circuits are connected together with jumpers. An ammeter is provided at each end of the locomotive to assist the driver in operating the controller, and he also has labour-saving devices within reach which, operated by means of push buttons, work the pneumatic bell-ringer, pneumatic sanders, main circuit breaker reset and pantagraph bow. The bell and sanders can also be operated by foot pedals, which are provided for further security.

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Fig. 5 shows the result of a test run made in actual service through the tunnel with a 900-ton train, and indicates very well the fluctuating nature of the load on the power house. The electrification of the line just described is a compliment to the single-phase system, as the entire electrical equipment had to be provided, and as all methods of electrification were considered by the engineers of the Tunnel Company each started on the same basis.

Having now described the principal features of some railways equipped on the single-phase system, the remainder of this paper is devoted to the consideration of the possibilities, advantages, and dis-

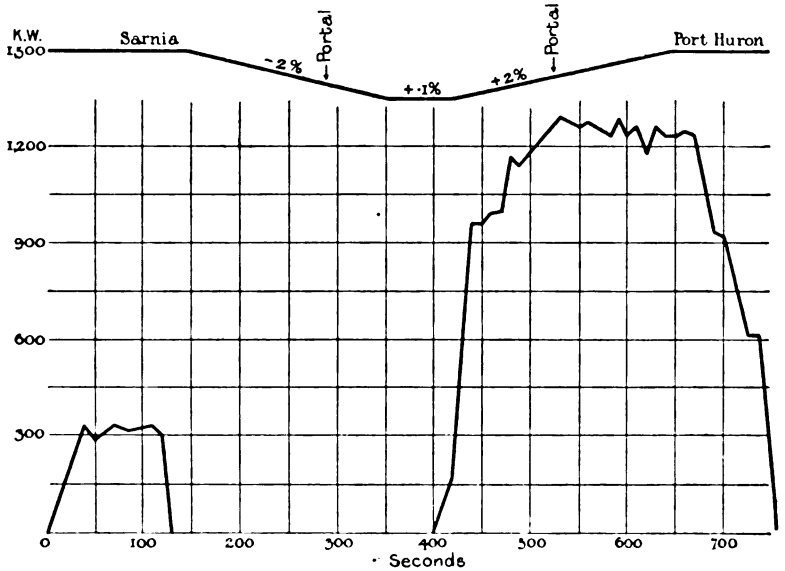

FIG. 5.—Curves showing Result of Test run with Double Header Locomotive drawing 900-ton Train through the St. Clair Tunnel.

advantages of the three systems which can be classified under the names of—direct-current, single-phase, and 3-phase.

The Direct-current System.—The street tramways were the forerunners of present heavy electric traction, and it has been universally admitted that a motor with characteristics of the series type is most desirable for that class of work.

The chief advantage of the series motor is that it exerts its greatest tractive effort at the lowest speed. In railway work the greatest tractive effort is required at the slow speed incident to starting, and when running at full speed a minimum tractive effort is needed. More tractive effort is required on grades and curves, and this is automatically obtained at the expense of speed. Since the series motor

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increases its tractive effort while decreasing its speed, the variation in the amount of power required at different points in any cycle is less than the variation in either tractive effort or speed. This feature tends to keep the load on the power house more even, which would not be the case with motors of the constant-speed type.

The exponents of all three systems are in agreement that a high voltage is in most cases desirable for economic reasons to be supplied to the train, and for long lines a high voltage is essential. Considering the length of time that the direct-current system has been in the field, its progress with regard to increase of voltage has been very slight, and especially so when it is remembered that in the same period power-transmission voltages have increased enormously.

In the earlier days of electric traction when the lines did not extend far from the source of current supply the trolley voltage was 450–500. This has gradually increased until 600 volts is common for railway working, and it is possible that 800 volts may be used. This voltage is about the maximum that can be applied to one motor, and for higher voltages two or more motors must be connected in series. Actual experience seems to indicate that motors of the type at present in general use have their safe working limit at 600 volts. The addition of commutating poles allows a further increase up to about 800 volts; but for pressures above this the motors must be put in series. From the motor point of view an increase of pressure means that better insulation is required, commutating troubles are more likely to occur, and if a flash-over between brushes happens to take place the results are very much more serious than on lower voltages.

Perhaps the maximum direct-current voltage is obtained by the use of the Krizik system in which two trolley lines are used, one being 1,500 volts above earth potential, and the other 1,500 volts below earth potential. Four 750-volt series motors are used in two groups of two motors connected in series. It is to a certain extent a 3-wire system, the rails forming the neutral and being connected to the mid-wire. It is only at starting, however, that the rails carry current, this resulting from the use of one trolley circuit only so as to obtain half voltage on the motors for starting purposes. For full-speed running the four motors in series are across 3,000 volts, so that each motor has 750 volts at its terminals.

It must not be overlooked that higher voltages require extra precautions for safety in the control gear, and although for a given power the current is proportionately less than for lower voltages, the gain in lighter switch contacts, etc., is more than off-set by the increased insulation required. As there are limits to the voltage on a direct-current railway motor, so there are limits to the voltage which can be supplied by a direct-current generator or rotary converter when operating on the fluctuating load which occurs in railway service. For suburban railways of large towns where a very dense amount of passenger traffic has to be handled on comparatively short lines, the direct-current system has advantages over its competitors.

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The proposition of electrifying any railway, apart from special problems of engineering, is not a technical, but a financial matter, and provided different systems will meet the requirements of the line, then the selection of the particular one depends on cost, considering both first cost and upkeep. As the 3-phase system is not suitable for suburban lines for reasons given later, the choice rests between the direct-current and single-phase systems. Broadly speaking, it is found that where a city has a large passenger traffic to its suburbs, the direct-current operation of the trains will cost less. This results from there being required a large quantity of rolling stock, and as the cost of a single-phase electrical equipment will usually be about one-third more than the corresponding direct-current equipment, the extra cost on a large number of single-phase equipments more than balances the cost of the rotating machinery sub-stations of the direct-current system. The generating station, assuming this to be of the 3-phase type with high-tension feeders to sub-stations, would be approximately the same for either system. Another point in favour of the direct-current system is the use of the third rail instead of the overhead trolley line. Whichever is used, repairs and inspection are continually going along; but as the train service is very frequent, it is practically impossible to inspect or repair an overhead trolley wire except during a few hours in the night. To do this requires a special night staff, and the work is of a less satisfactory nature than if done in daylight. With the third rail inspection can be made at all times, and some repairs can be made without stopping the train service, the work being done by the permanent-way staff.

The single-phase system will now be considered.

The advent of the single-phase commutator motor has provided a machine having the desirable characteristics of the direct-current series motor without in any way limiting the voltage at which current can be supplied to the train. There are a number of types of this motor differing from one another in their method of connections, but so far as railway work is concerned there are two principal types which are shown diagramatically in Fig. 6. These can have minor modifications which do not, however, influence their principle of operation to any great extent.

A is the compensated series motor.
B is the compensated repulsion motor.

The former type is the one most largely used, and gives a simpler and slightly lighter machine than the latter, the principal claim of which is that higher voltages can be put directly on the motor. This point is of little practical value as the increase is not sufficient to enable the high voltages which it is desirable to use in single-phase working to be directly applied to the motor. A step-down transformer has to be used which is equivalent to the auto transformer of the compensated series motor.

By the use of the auto transformer a most desirable feature in

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railway working is obtained. This is that a low voltage can be used on the motor however high the trolley voltage may be above ground potential. On any railway system a large proportion of breakdowns occur through insulation failure, and as the full voltage ever applied to the alternating-current series motor does not generally exceed 300 volts the chances for trouble in this direction are decreased. From this it will be seen that while increase of supply voltage on the direct-current system necessitates an increase of voltage on the motor, which is undesirable from every point of view, yet the increase in single-phase supply voltage does not necessitate any increase of pressure on the motor. The high-tension circuit being confined to a single path—*i.e.*, from trolley through the auto transformer to ground—can be well isolated from the rest of the electrical equipment, so that in addition to the motors the control gear also works on a low voltage.

Another advantage over the direct-current system is that every

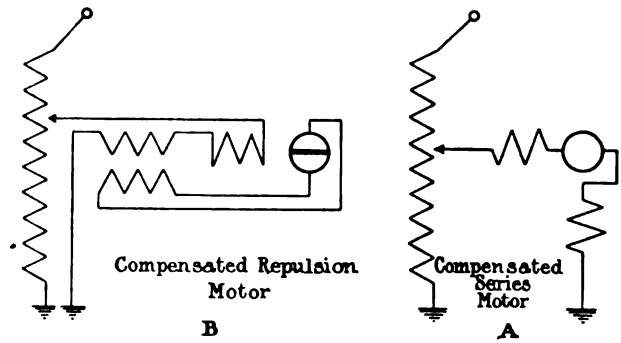

FIG. 6.

variation in the voltage applied to the motor, is obtained from tappings to the auto transformer winding, and not by the insertion of ohmic resistance into the circuit with its accompanying losses.

It is often stated as an argument against the single-phase motor that it gives an intermittent draw-bar pull. A little consideration will show that this does not result in actual practice. The motor frame being spring suspended does not provide a perfectly rigid take-off point from which the torque is exerted, and there is a certain amount of give in the motor shaft, gears, and axle; there is also the inertia of the revolving parts to be taken into account. Now as the current alternates so rapidly and there are the spring and inertia effects to smooth out the torque variations, it is not possible that any detectable variation will reach the rim of the driving wheels. This is quite borne out in practice by the draw-bar pull of single-phase locomotives being as high per ton weight on the driving wheels as for direct-current equipments. In a steam locomotive the torque variation does produce slipping much more easily than with any electric motor, but in this

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case the alternations are at a very slow rate compared with those of the single-phase motor, and the drive is more rigid.

In the generating and transmission of the power there is no moving machinery between the generators and the motors in the train, all pressure changes being obtained by transformers, and as these are more efficient than the rotating transforming machinery for direct-current supply and also do not require as much space or attention, this forms an advantage for the single-phase system. Comparing the efficiency of both systems the advantage appears to lie with the single-phase when the whole of the plant involved is taken into consideration. Comparing the rolling stock efficiencies alone the direct current is higher due to the electrical equipment being lighter. If, however, the train is frequently started and stopped or speed variation is required, as in freight service, then, due to the absence of rheostatic losses on the alternating-current system, the efficiencies might be equal or in favour of the alternating-current system. The alternating-current trolley losses when a suitable voltage is used would be less than the direct-current third-rail losses, and the higher efficiency of the single-phase system sub-stations would in most cases alone make up for the increased weight of the alternating-current rolling stock, even if the starting and stopping was infrequent and no speed regulation required. The sub-station feeder losses would be the same in either case. In the power station less total output would generally be required for the single-phase system. In some cases, of course, the power station could feed the alternating-current trolley direct, where on the direct-current system sub-stations would be essential. It has been mentioned that the alternating-current electrical equipment is heavier than the equivalent direct-current equipment, and where the latter is expressed as a percentage of the former it may through misconception be applied to the percentage difference of the train weights which have to be moved at the expense of the electrical energy. This is incorrect, of course, as the electrical equipment forming only a portion of the train weight will cause less percentage difference in complete train weights than between electrical equipments alone. As at present most heavy suburban electric traction is worked on the direct-current system, the fact that alternating-current single-phase equipments can also be operated by direct current will for the immediate future be very convenient.

A few points of the 3-phase system will now be considered.

Three-Phase System.—The motor used on this system is of the poly-phase induction type, which tends to give constant speed at all loads. This is one of the features which limit the use of the 3-phase system to particular cases of electric traction. It has already been described why the series characteristic is desirable in railway motors, and it may now be pointed out that the 3-phase motor gives a torque which is directly proportional to the power supplied irrespective of the motor speed. Without considering the motor losses, the power supplied at full speed appears as useful output, but at half speed the same amount

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of power has to be supplied, half of which is wasted in heat and the other half appears as useful output. At one-tenth speed nine-tenths of the power supplied are wasted in heat. This undesirable feature of the 3-phase motor is partly overcome by using two or more motors connected together in "cascade" or "tandem." In this method the main motor has its stator winding connected to line and its rotor winding feeds the cascade motor. With two motors so connected the combination practically acts as one motor with twice the number of poles, and thus half speed is obtained. Lower speeds are obtained by regulating the resistance in the rotor circuit of the cascade motor. Above half speed the cascade motor is cut out and runs idle, the gradual increase to full speed being effected by cutting resistance out of the rotor circuit of the main motor.

Another method by which different speeds can be obtained is by altering the field connections to obtain different numbers of poles. It is evident, however, that whichever method is used the number of efficient running speeds is limited. When full speed is obtained it will tend to keep constant whatever the gradient of the line may be, and so throw a very variable load on the power house. There is no possibility of running faster to make up lost time, but there is also no possibility of racing downhill. The efficiency of acceleration for 3-phase motors is not comparable with that of alternating-current or direct-current series motors, and where the accelerating period is considerable in the cycle of operations as happens for city and suburban work, this point counts against the 3-phase system. The direct-current series motor when giving constant acceleration ultimately reaches a point at about 60 per cent. of the free running speed where it can be connected to the supply without resistances in circuit, and from this point the acceleration gradually decreases, and at the same time the current decreases until constant speed is reached. In the single-phase alternating-current motor this point occurs at 40 per cent. of the free running speed, and so on both types of series motor the peak load demand is less than with the 3-phase motor which requires the accelerating current maintaining a full value until full speed is reached. Since the induction motor tends to run at practically constant speed for all loads, if two motors are working together and there happens to be a slight difference in their driving diameters due to wear, then the load will not divide equally. To overcome this difficulty adjustable resistances are connected in the rotor circuits by which the load can be made to approximately equalise. The 3-phase system requires two overhead trolley wires which are at different potentials, and so it is a difficult proposition to arrange the lines at crossovers and in shunting yards; it also tends to limit the voltage which can be safely used. An advantage of the induction motor is its ability to return power to the line when run slightly above synchronous speed. The advantage is not so much from the point of view that power is returned to the line, as this is undesirable in some cases, but the motors acting as generators form an efficient brake for safely descending long grades. It is only fair to

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note, however, that the direct-current and single-phase motors can also be arranged to regenerate. Although this system is handicapped by the necessity of using two overhead wires, and in some cases by the characteristic of the induction motor, yet for mountain railways and straight point-to-point runs as in tunnel haulage for steam lines, it has a field. There is no doubt that the introduction of the single-phase series motor has reduced the sphere of operation of the 3-phase system, but at present there is room for both. When railway electrification becomes more general and standardisation is necessary to effect inter-running of different lines one system will have to be used, and unless some radical change takes place the general suitability of the single-phase system for all classes of railway work tends to point to the adoption of that system.

In conclusion, I must thank the following firms for the information they kindly placed at my disposal: The British Westinghouse Electrical and Manufacturing Company, Ltd.; The British Thomson Houston Company, and the G. E. Company of U.S.A; Messrs. Siemens Bros., Dynamo Works, Ltd.; The Electrical Company, Ltd., and the A. E. G. of Berlin; and The Lahmeyer Electrical Company.

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THE DIRECT-CURRENT VARIABLE-SPEED MOTOR AND ITS APPLICATION TO MODERN MACHINE TOOLS.

By W. STANLEY LONSDALE, Student.

(*Abstract of paper read before the* STUDENTS' SECTION *in London, February* 3, 1909).

INTRODUCTION.

The want of a really good type of direct-current shunt-wound variable-speed motor has been felt very considerably in the past, and now that the demand for these machines has increased lately to a large extent, due chiefly to the more universal use of high-speed tool steel, the author proposes to review the gradual development in high-speed working that has been brought about by the conjunction of this type of motor and the high-speed tool, and then to consider the three following propositions :—

1. Possibilities with high- and variable-speed working.
2. The design of a motor to meet the conditions imposed by above.
3. The useful sphere in which motors of this class can serve, with reference to machine tools.

It is only in recent years that "individual" or "grouped" drives have been looked upon with much favour. This has been due almost entirely to the fact that it did not pay to drive individual tools each with their own motors unless the tool was a very large one. The advantages gained by the individual drive are briefly as follows :—

1. *Increase in Output* due to elimination of long drives and shafting, resulting in saving of power and friction load, and the possibility of working the tool up to its limit.
2. *Improvement in Quality of Work* due to steadier and smoother running.
3. *Separate Working.*—Overtime working on a section may be arranged for without running the whole shop.
4. *Testing Power Consumption.*—By means of, say, a portable ammeter, a check can be kept on the power taken by a whole shop, section, or individual tool.
5. *Increased Facilities for Extensions to Works.*—This is possible as the original drive need no longer be taken into consideration.

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On the introduction of high-speed tool steel the speed of working was increased in order to take the fullest advantages the steel offered. This naturally increased the power required by several of the machines, and difficulties were experienced with the belts, as these could not, owing to their size, be easily shifted on the cone pulleys. A lot of power was also lost in slip and extra bearing friction, the net results being great wear and tear on the belts, frequent bearing troubles, with consequent high maintenance charges for the plant. Further, on account of a variety of mandril speeds required in a number of the operations, there was difficulty and great waste of time in belt and gear changing. Several variable-speed counter-shaft gears were brought out and tried, but these met with little or no success. Bearing in mind the above, if we now dispense with the cone pulley and do away with the cumbersome change-speed gears for large head stocks, it is clear that a variable-speed motor to cover the whole range of lathe speeds is the only suitable substitute.

Possibilities with High- and Variable-speed Working.

We have two classes of tool steel :—

(*a*) Water hardened (carbon steel).
(*b*) Air hardened (self hardening).

It was in 1860 that Mushet discovered the latter, and in the course of his experiments, which have now become of such service to mankind, he found by adding manganese and tungsten to the steel, that the tool was able to retain its cutting edge at a much higher temperature. It was not until later, however, that Taylor and White took the question up and conducted a long series of tests on tungsten steel at the Bethlehem Steel Company's Works in Pennsylvania.

The great point brought out by Taylor and White was, that although ordinary air-hardened steel was spoilt by heating up to a greater temperature than that equivalent to a "cherry red," if additions were made of manganese, tungsten, and other like substances in definite proportions, it was possible to obtain an improvement in the cutting qualities of the tool at much higher temperatures. When this matter was taken up more generally in this country it was found that the results obtained were so different and opinions so very conflicting that some doubt was expressed as to the practical value of Messrs. Taylor and White's investigations. The Berlin Verein Deutscher Ingenieure carried out some exhaustive tests to settle the matter once and for all.

In 1902 Dr. Nicolson started a series of special tests at the Manchester Municipal School of Technology, on the new steel, when working in Whitworth fluid pressed steel and cast iron. Tests were taken with soft, medium, and hard samples of each.*

The Berlin experiments were conducted with tools intended to last *one hour*, while the Manchester experiments, the "economical time,"

* See Report to Manchester Association of Engineers, October 24, 1903.

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was taken as 20 *minutes*. From these tests the formula found most closely to represent the relation between speed and area was—

$$V = \frac{K}{A + L} + M.$$

V = Cutting speed in feet per minute.
A = Area of cut in square inches.
K, L, and M = Constants (functions of tool and steel hardness).

In working at these high speeds we are dependent upon a number of variables, and the numerical values for the constants, K, L, and M above, referring to the materials operated upon, are given below in Table I.

TABLE I.

Constant.	Fluid Pressed Steel.			Cast-iron Bars.		
	Soft.	Medium.	Hard.	Soft.	Medium.	Hard.
K	1·950	1·850	1·030	3·100	1·650	1·300
L	0·011	0·016	0·016	0·025	0·030	0·035
M	15·000	6·000	4·000	8·000	7·000	5·500

The most important of these variables is the hardness of the casting or forging, the hardness of the tool, and the radius of the tool nose. The relation between cutting speed and area of cut is given by the formula—

$$V = \frac{1}{a} + 15,$$

V = Cutting speed in feet per minute,
a = Area of cut in square inches,

deduced from the Berlin and Manchester experiments. This formula is for the speed at which a given cut is assumed to be taken under ordinary workshop conditions, and at which the heaviest cut for which a lathe is designed must be taken. The results obtained at both tests were found to come well inside the limit curve, except a few of the Berlin light cut curves.* It must be borne in mind, however, that the "economical time" for the Berlin tools was *one hour*, and Manchester 20 *minutes*. The Manchester "soft steel" specimens were in reality very tough, and, as suggested by Dr. Nicolson, the constant given in the formula above may be considerably increased for ordinary steel met with in practice, without endangering the tool.

* See Nicolson and Smith's "Lathe Design."

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Once having obtained the area of cut we settle on a suitable speed, the economical life of the tool having been previously fixed. The force required for taking the cut can be determined, and the approximate net horse-power can then be calculated.

Methods Employed for Driving Tools.

Before passing on to other things perhaps it would be as well to enumerate the means adopted for main-driving in electrically driven tools, in order that a correct classification may be made and no confusion caused. There are three methods :—

1. *A Constant-speed Motor* used with a tool fitted with an all-gear head, containing gears of different ratios, these gears being apportioned to suit the class of work the tool has to deal with.
2. *A Variable-speed Motor* in place of a cone pulley to give continuous variations in conjunctions with the all-gear head as above.
3. *A Variable-speed Motor* to cover the whole range of speed, the motor being arranged for a direct positive drive.

It is proposed in this paper to deal only with the two latter, referring specially to the last method.

Speed Control for Variable-speed Shunt Motors.

There are several methods which may be employed for obtaining speed variations on shunt machines :—

1. By adjustment of the shunt field strength by means of a shunt rheostat.
2. By varying the pressure supplied to the armature circuit by means of a series rheostat.
3. By the double or multiple voltage system.
4. By double commutator machines.

The first of these is the one that it is proposed to consider to-night. The second method is rarely used, as it at once destroys the most important feature ; the speed varying to a great extent under fluctuating loads. Further, in the case of large motors this is very costly, as the rheostat is expensive on account of its size and the method inefficient on account of great waste of power in the resistances. The third only applies in cases where the power required is reduced as the speed is reduced. The arrangement of double or treble wiring is not always feasible, and any advantage which may be gained on this score is mitigated with the advent of the commutation pole and compensating winding. The fourth is only applicable to machines where constant torque is required—*e.g.*, pumping plants—as the machines give the same torque with the commutators in series or parallel ; and further, as with

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the third system, it is not possible to get full power at low speeds. With the commutators in series, only half the power is available as when in parallel. Further, on a 500-volt system special attention has to be paid to the insulation of the armature, as there is double the voltage between adjacent coils.

The Design of a Shunt-wound Variable-speed Motor.

Two main problems limiting the output of the motor have to be faced :—

(*a*) The heating at the minimum speed.
(*b*) The sparking at the maximum speed.

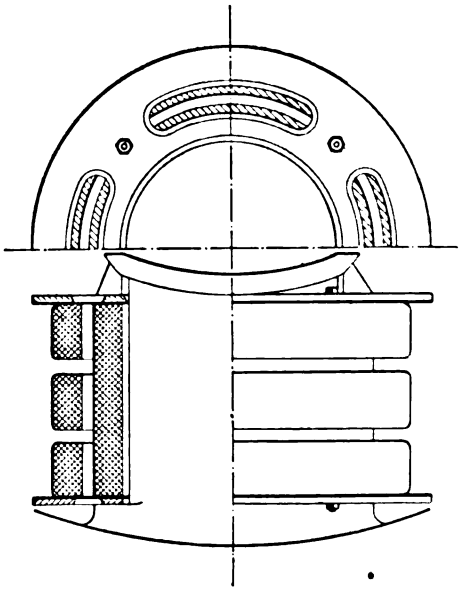

Fig. 1.—P.D.M. Ventilated Coil.

In proportion as these two problems can be suppressed the weight and cost of a machine can be reduced for a given output. With a modern machine of any high-class design the efficiency is about as high as it is possible to obtain with the present materials employed in manufacture. Our attention must perforce be turned towards the reduction of heating and improvement in commutation.

(*a*) With regard to the first of these two special attention must be paid to the ventilation of both field coils and armature, an easy path being provided for the flow of air through the machine.

With the introduction of the commutation pole and a compensating winding in the main pole-face, the matter of keeping the field system

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cool is no longer an ordinary problem, but one which has to be carefully studied.

The Phœnix Dynamo Manufacturing Company have patented the use of a special ventilated main coil. This coil is wound in two parts, as shown in Fig. 1, each portion being on a separate spool, the two spools being separated by air ducts.

The fan action of the armature drives the air through these passages and gives very efficient ventilation.

The curves in Fig. 2 show a test result obtained on one of the coils in comparison with an ordinary coil.

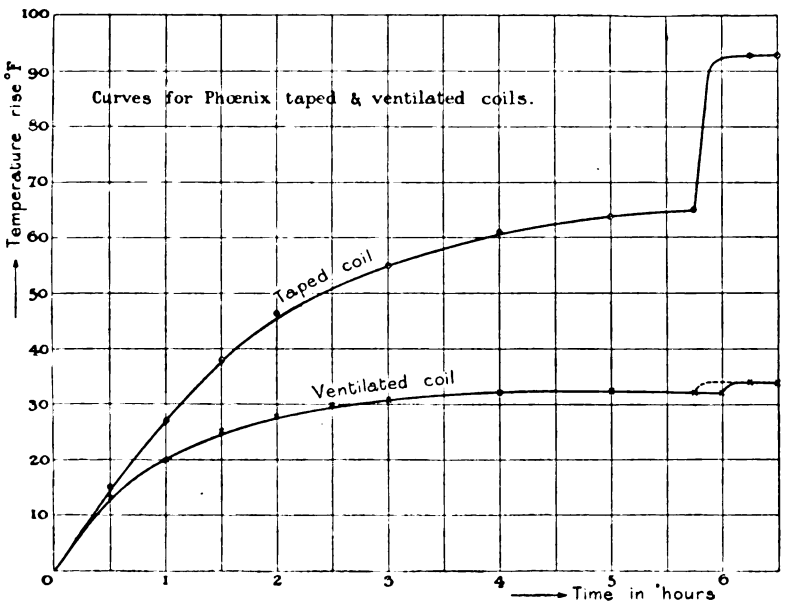

FIG. 2.

It will be noticed that with the ordinary coil the external temperature rose to about double that of the ventilated coil, while on stopping the machine the temperature rose still higher on account of the absence of windage, showing that the internal temperature was much higher than that of the ventilated coil. When applied to standard carcases this method of cooling coils has, in the author's opinion, a serious drawback, for when the coils are fitted to machines such as variable-speed motors with commutation poles in providing these ventilating passages the diameter of the coil is increased, thereby filling up the space round the commutation pole, preventing free circulation of air, and also limiting the winding capacity. For plain shunt or compound machines the idea is undoubtedly a good one.

(*b*) The question of good commutation at high speeds is a much

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more intricate problem. With workshop motors it is absolutely essential that the brushes remain in a *fixed position* whatever conditions of load and speed there may be. For high-speed and variable-speed working several methods have been tried to achieve this, and those employed at the present time are as follows:—

1. Using commutation poles.
2. Using a compensating winding.
3. Using a combination of commutation poles and compensating winding.

It should at first be carefully borne in mind that, other things being equal for a given speed range, the size of the motor must be increased in proportion to the speed range. Commutation poles do not enable a small motor to give a big output at a slow speed, their adoption being to secure good commutation qualities at high speeds when the main pole flux is weak. It is usual in designing a direct-current motor to calculate the "reactance voltage," as this determines whether a machine of a given design will commutate its current sparklessly or not. A method which is very generally used by designers is that proposed by Mr. Hobart,* the change in current in the armature coil during the commutation interval being assumed to follow a sine law. The reactance voltage is $e = 2\pi n L c$, where n = equivalent frequency of reversal,

$$\text{and} = \frac{\text{peripheral speed of commutator}}{2 \times \text{brush thickness}}$$

L = Inductance of the coil in henries.

c = Current in coil in amperes.

With regard to the calculation of the L, Mr. Hobart has put on record by means of tests on slots having a ratio of depth to width of 3 to 1 that for slotted armatures a conductor embedded in the slot has 4 lines/cm. per ampere, and that the end connections have 0·8 lines/cm. per ampere.

Commutation Limits with Variable-speed Motors.

If we are to obtain good commutation with variable-speed motors having wide speed ranges without the use of *any* of the above-mentioned devices we must rely entirely upon the brush resistance to effect the reversal of the current.

Low reactance voltages may be obtained with big commutators, but if a large speed range is required it is necessary to have a very strong main field, and also the ratio of pole-arc to pole-pitch must be smaller than with an ordinary machine.

The author has obtained during ordinary testing work a speed variation of 4 to 1 with a 250-volt motor of ordinary standard design, no commutation poles being fitted, the commutation being excellent.

* Parshall and Hobart, "Electric Generators."

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With a 500-volt motor, however, the difficulty presents itself of obtaining a low reactance voltage at the high speeds, and one or other of the above methods must be resorted to.

1. *Commutation Poles.*—This method is to place a small auxiliary pole midway between the main poles. These poles are series poles through which the main current, or a portion of it, passes. The addition of these poles to a machine is to produce a reversing magnetic field for the coil undergoing short circuit by the brush. This field sets up in the coil an E.M.F. in direct opposition to the coils' own reactance voltage. In the Phœnix machine the pole-faces are arranged to decrease in breadth in the direction of rotation, and it is claimed that this arrangement, brought out by Dr. Pohl, equalises the field distribution.

2. *Compensating Windings.*—The idea of having a cross-compound winding having auxiliary series coils set to produce a field at right angles to the ordinary field was originally put forward by Menges in 1884, and at the same time he suggested the winding of these coils round the pole-pieces. Later, Fischer-Hinnen proposed the winding of the coils in a slot notched in the centre of the pole-face. A more complete solution of the problem, however, occurred to Ryan,* who arranged a number of coils embedded in slots cut parallel to the shaft in the pole-face; this method was patented by him in 1893. The matter was for some reason or other not taken up until later, when Deri revived the idea, using as a field-magnet system a laminated structure resembling the stator of an alternating-current machine, and which we now see embodied in the Brown-Boveri type of direct-current turbo-generator. The matter was brought into prominence in this country in turbo-work by a patent which Messrs. Parsons took out in 1903 for a similar winding.

Combination of Commutation Poles and Compensating Windings.

With this arrangement an undistorted field system is produced, and at the same time a reversing field for the coil under short circuit.

The Type of Winding to be Adopted.—There is considerable diversity of opinion as to the advisability of using commutation poles, a compensating winding, or a combination of the two for high-speed machinery, and for motors where there is a big voltage variation on the commutator due to a wide range of speed. Messrs. Parsons, for their direct-current turbo-generators, advocate a compensating winding only, arranged for 2 to 2½ times the ampere-turns on the armature. With this arrangement there is sufficient margin both to neutralise the armature reaction, and also to provide a commutating field for the coils under reversal. In a paper read last April by Messrs. Stoney and Law before this Institution the authors laid great stress on the point that in the absence of the commutation pole, there is no "time lag" due to self-induction, when the machine is working on rapidly changing loads. This "time lag" in the saturation of a commutation pole is very

* See article by Fischer-Hinnen, *Electrician*, vol. 40, p. 382, 1897–8.

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much augmented by the presence of ordinary diverting resistances in parallel with the commutation winding, these having a much smaller coefficient of self-induction as compared with the iron circuit, a relatively greater flow of current will pass through the diverter on sudden overloads, and consequently the commutation pole flux will be weakened and sparking will occur owing to the reversing field not being strong enough. This difficulty may be overcome by using an inductive diverter. With this regulator the resistance material is wound on a laminated iron core, and as the air-gap of this core is capable of adjustment it is thus possible to arrange that the inductance of the commutation pole circuit shall equal that of the diverted circuit, and so an equal "time lag" for both circuits is obtained. It is, however, not convenient to have additional regulators or motors installed in workshops, and the best way, when designing the motor, is to allow for slightly more ampere-turns on the commutation poles than is found by calculation to be necessary, and also to have a large air-gap. It is then possible to adjust the machine on test, either by removing a few of the turns per pole, or shortening the air-gap, by putting plates behind the poles. There is no doubt whatever that variable-speed motors can be built to give sparkless commutation over the whole speed range when compensating windings or commutation poles only are used, but it will be seen at once that with the use of compensating windings alone it is quite possible on a sudden variation or increase of the load to obtain a field distortion in the opposite direction, and so cause the machine to flash over. If a combination of both windings is made it is possible to effect a complete neutralisation of the armature reaction.

Flash-over Limit.—It is generally found that with ordinary commutators, if the volts per segment rise to a higher value than 50, there is danger of a flash across the brushes. This is dependent, to a great extent, on the state of the commutator; for if this is dirty, and there is any deposit of copper or carbon dust, the machine is liable to flash over at a much lower figure than that given above. The author has stood by motors which have been overloaded purposely to find limits, etc., and examined the commutator through a sheet of ruby glass. When the "flash-over" point is reached, besides the excessive sparking under the trailing edges of the brushes, sparks are frequently noticed to start from adjacent segments between the brushes, these being segments first entering the commutation field, the sparks eventually linking up and causing a flash round the commutator.

A Large Variable-speed Motor.

A very interesting example is a motor designed by Messrs. Siemens Brothers Dynamo Works, Ltd., to drive a 60-in. centre Buckton gun-lathe. It is capable of developing a 100-B.H.P. on a 500-volt direct-current supply, with a speed variation of 6 to 1 (namely, 100 to 600 revs. per minute), the machine being able to give its full output over this speed range. This motor is the largest of

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its kind built for such a wide range of speed. The lathe is arranged for a direct-geared drive from the motor; and, as is usual with these big lathes, the feed and speed of cut is effected from a control platform, these motions being taken from a smaller variable-speed motor

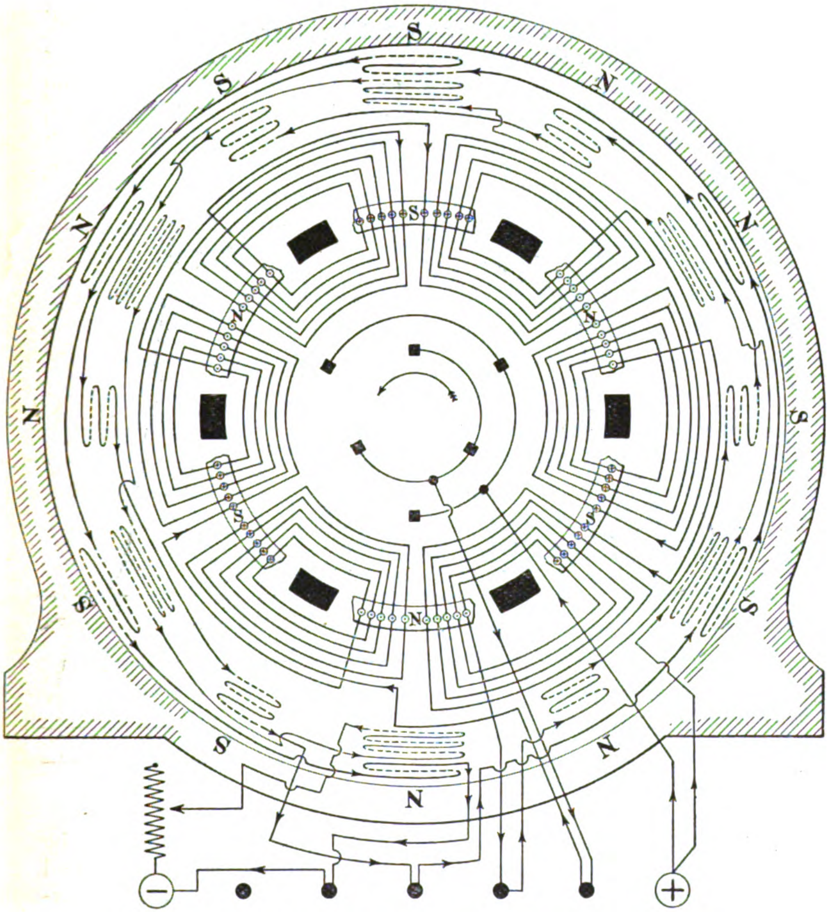

FIG. 3.—Diagram of Connections.—Siemens 100-B.H.P. Motor.

at the far end of the lathe-bed. The speeds may be varied at will over the whole range without the operator having to leave the job by placing the two shunt regulators belonging to these machines on the control platform.

The motor in question has 6 main poles, and is also fitted with commutation poles and a compensating winding. It is shunt-wound,

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except for one series turn pole, which was added in order to improve the stability under working conditions. Fig. 3 shows the scheme of connection of this motor. The yoke is a rigid construction of cast iron. The main poles are rectangular and laminated throughout (*i.e.*, pole and shoe), the plates consisting of 1 mm. steel papered on one side. The commutation poles are also laminated and provided with stiffening plates, the core being riveted together.

There is no doubt whatever that "cast-in" poles are a source of frequent trouble in the magnetic circuit, due to air-bells collecting behind the poles when the cast-iron yoke is poured. A further point, which will be appreciated by all, is that the entire field system of both

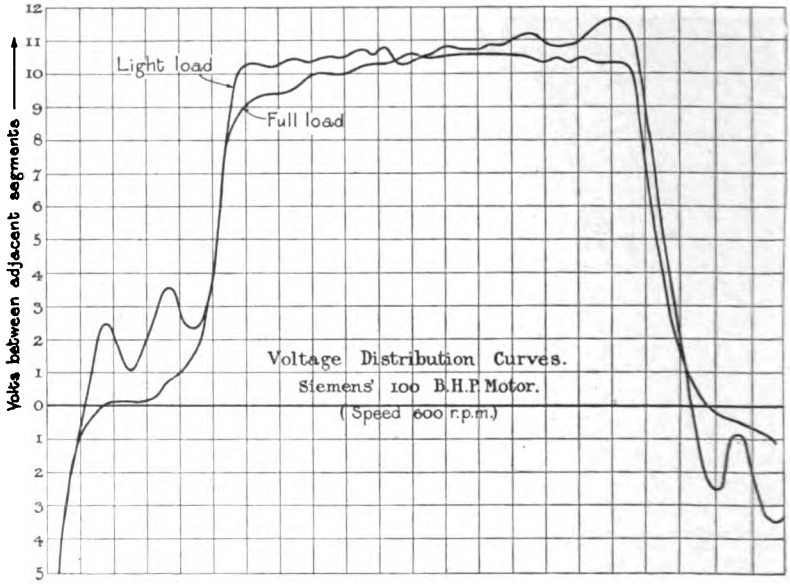

FIG. 4.

main and commutation poles, or any individual field coil, can be removed without dismantling the machine beyond removing the end shields. Both the main and commutation field coils are former-wound, the whole coil being mounted on a rectangular bobbin. The series turn located at the back of each shunt coil consists of strip copper, the strips being bent round a former, and then taped together to form a complete coil. The compensating winding consists of solid copper strips, each taped and imbedded in slots in the pole-face. The strips are connected up at the hang-out, by sweating into a copper shoe, making a very solid joint. The armature is of the slotted drum type, built up of soft iron laminations of a very low hysteresis loss iron; the stampings are mounted in a cast-iron spider keyed to the shaft.

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The commutator, before machining, is subjected to a heavy pressure, and then mounted on its own hub, which is then keyed to the same spider. The armature coils are former wound and interchangeable, the coils being held in position throughout their entire length in the slots by means of wedges of a hard wood dove-tailed into the teeth.

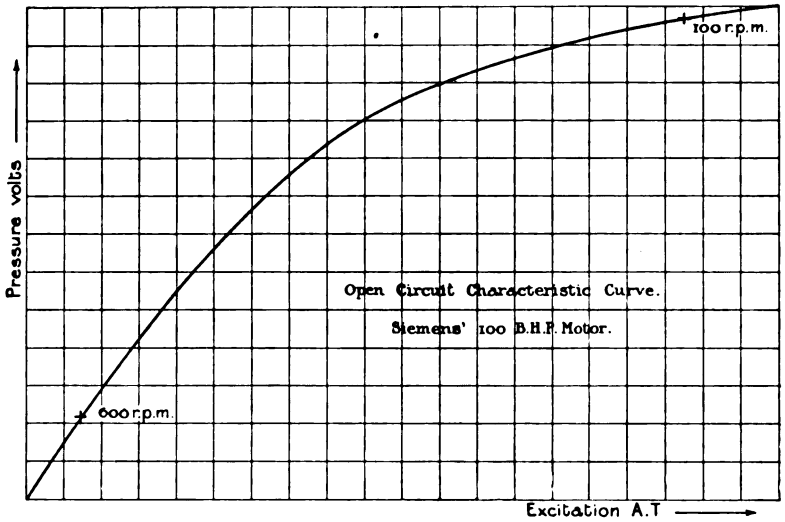

FIG. 5.

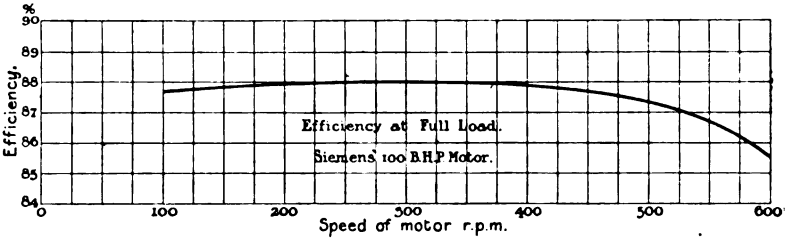

FIG. 6.

TESTS.

The highest temperature rise recorded after a 5 hours' run at full load at 350 revs. per minute was only 37° F.

Fig. 4 shows two curves taken on the machine giving the pressure in volts between adjacent commutator segments at different points on the pole-pitch line. Both these curves were taken at the maximum speed (600 revs. per minute) one at full load and the other at light load.

Fig. 5 shows the open-circuit characteristic curve of the motor.

The efficiency of the motor at full load is shown plotted against the speed in Fig. 6. It will be noticed that the maximum value reaches

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some 88 per cent., and, further, the curve remains fairly flat over the whole speed range. When on test the motor was found to be perfectly stable from no load to 100 per cent. overload at all speeds. This is, of course, a very important point to be achieved in the design of a variable speed motor, especially when driving machine tools, as all hunting is eliminated when starting and stopping a cut. It was not possible to detect *any* sparking from 100 to 600 revs. per minute, and the commutator was found to be in excellent condition after the above-mentioned test.

A smaller variable speed motor was also designed for actuating the control platform of the lathe, capable of giving 5 B.H.P on a 500-volt direct-current circuit from 150 to 1,020 revolutions per minute. This motor is *not* provided with a compensating winding, but it has commutation poles.

Fig. 7 gives the voltage distribution curves taken on this machine at

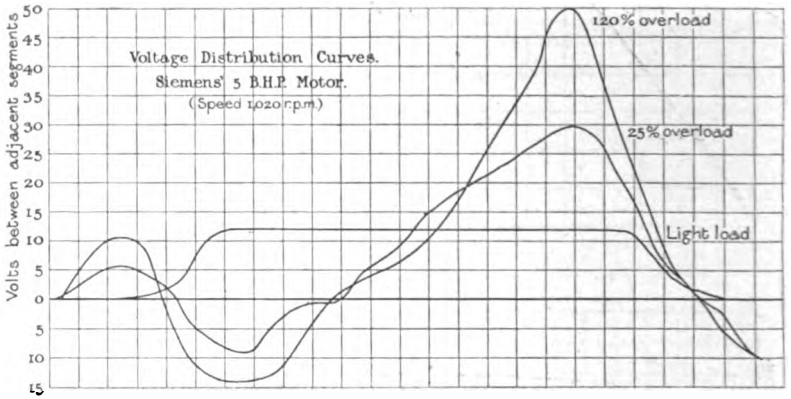

FIG. 7.

light load, 25 per cent. and 120 per cent. overloads at the maximum speed, 1,020 revs. per minute. If these curves are compared with those taken on the 100-B.H.P. motor, Fig. 4, it will be noticed at once how the compensating windings act to reduce the distortion of the pressure curve, and also in the absence of these windings how the armature field action effects the volts between adjacent segments. It will be seen that when this motor is working at 120 per cent. overload the volts per segment have reached the value of 50, and it has been found that at this point there is a great danger of a flash-over.

Fig. 8 shows the open-circuit characteristic curve of the motor.

CONCLUSION.

Machine tool-makers are just beginning to realise the important advantages offered by the direct-current shunt-wound variable-speed

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motor. By judicious selection, cases of antiquated drives and change-speed gear-boxes may be investigated, and direct-coupled motors installed. Difficulties which at first seemed insurmountable have been overcome by the application of the latest windings and mechanical construction. A wide field has been opened for these motors now that high-speed steel is finding a footing in most of our workshops, and judging from some of the excellent results obtained in recent installations the electrical engineer has not been found wanting.

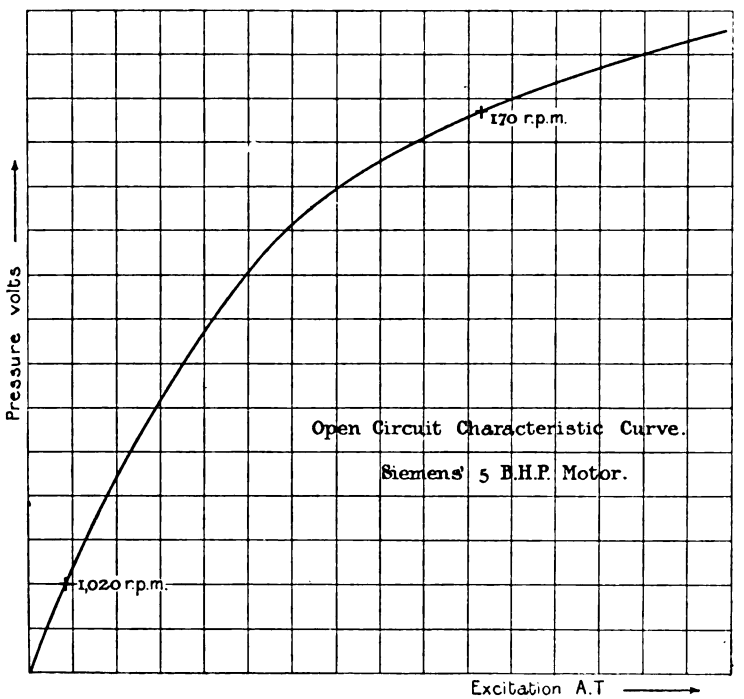

FIG. 8.

In conclusion, the author wishes to express his best thanks to Messrs. Siemens Brothers, Dynamo Works, Ltd., for the many facilities they have afforded him during the preparation of this paper; to Messrs. Lawrence Scott & Co., and Messrs. The Phœnix Dynamo Manufacturing Company, for their notes and illustrations which have been kindly placed at his disposal, and also to several of his colleagues who have assisted from time to time with their advice and suggestions, amongst whom should be especially mentioned Mr. J. K. Catterson-Smith and Mr. A. F. Campbell Pollard.

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THE UTILISATION OF EXHAUST STEAM FOR ELECTRIC DRIVING.

By C. S. RICHARDS, B.Sc. Tech., Student.

(*Abstract of Paper read before the* STUDENTS' SECTION *at Manchester, February* 18, 1909.)

Up to the present time this subject does not appear to have been touched upon by any of the papers read in connection with the Institution; but as it is of growing importance, and particularly to electrical engineers, a discussion of the subject should be of interest, and it is hoped that this paper will serve a twofold purpose.

1. To bring home to electrical engineers in particular the great importance of the subject by pointing out that the utilisation of waste steam means in most cases the adoption of the electric drive, and by showing that the extreme simplicity, reliability, low first cost, and almost negligible running costs, which are obtained by the installation of a low-pressure turbine plant, render it eminently suitable for the generation of electricity.

2. To show that it is not only of importance in extending the use of electricity in mines, rolling mills, etc., where waste steam is available, but that it may lead to large economies in ordinary central station work, and in power houses generally, where reciprocating engines already exist.

SECTION 1.

The only economical method of using the exhaust steam from non-condensing engines is to put down a turbine, which, acting as it does on a dynamic principle, can utilise low-pressure more efficiently than high-pressure steam.

The high speed of the turbine limits its application to the direct driving of electric generators, turbo blowers or exhausters, and turbo pumps, and of these the first, namely, the electric drive, has immeasurably the largest field.

Power Available.—The great amount of power available where engines are run non-condensing is seen clearly from the entropy diagram Fig. 1, which shows that the turbine will develop *approximately the same horse-power* as the engine from which it draws its steam.

Reliability.—The general reliability of this system is proved by its rapid and successful development; and indeed this may naturally be expected because the low-pressure turbine possesses the following distinctive characteristics in its favour:—

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1. A very short and stiff spindle.
2. Long blades which allow of relatively large clearances with small leakage losses (this applies more especially to the Parsons type).
3. No dummies.
4. No distortion due to difference of temperature in various parts of the casing.
5. No danger if the turbine goes over to atmosphere.
6. No part of the machine subject to high-pressure steam.

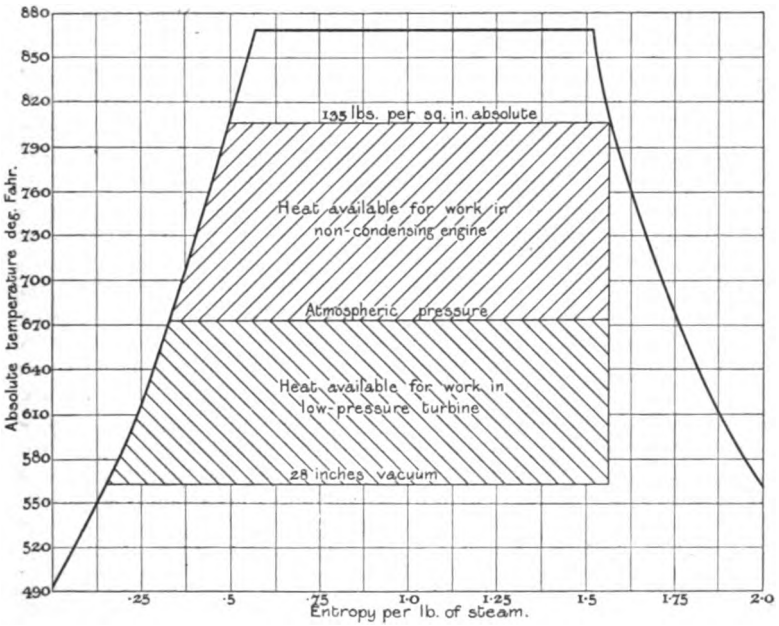

FIG. 1.

It will therefore be seen that the manufacture of low-pressure is a much simpler proposition than the manufacture of high-pressure turbines using superheat, and as the leading makers of the latter are turning out machines quite as reliable as ordinary steam engines, it follows that they should be able to manufacture low-pressure turbines, which are practically immune from breakdown.

General Description.—Nearly all the makers of the Parsons type of turbine in this country, on the Continent, and in America, have reverted to the double-flow principle for their exhaust machine. This gives an extremely simple construction. The spindle is made in one diameter and no dummies are required.

Turbines built on the impulse principle are all single-flow machines,

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and the method of construction is practically identical with that of high-pressure turbines, but, of course, since the high-pressure portion is cut out the number of wheels is greatly lessened and the machine is thus very much shortened up.

Roughly, an exhaust steam turbine may be considered to be the low-pressure portion of a high-pressure turbine giving double the output; and high- and low-pressure turbines of the same output should be approximately the same weight.

Mixed Pressure Turbines.—In cases where the exhaust steam available is insufficient to cope with the whole of the load, a very satisfactory method is to put down what is known as a mixed pressure turbine, *i.e.*, an ordinary high-pressure turbine, with the low-pressure end modified, provided with an opening in the cylinder at the point corresponding to a little below atmospheric pressure on full load, the high-pressure steam being passed through the turbine in the usual way, and the low-pressure led in at the point mentioned, the valve and governor gear being so arranged that the machine will work automatically either on high pressure alone, low pressure alone, or on high and low pressure together, according to the quantity of exhaust steam available at the moment.

A turbine of the Westinghouse-Parsons type, of 368-k.w. capacity, installed at the Gloucester Railway Carriage and Wagon Company's Works, Gloucester, is fitted with high- and low-pressure steam chests, the latter being capable of passing 9,000 lbs. of exhaust steam per hour, which is the maximum quantity available, and from which 210 k.w. are obtained, the rest of the load being carried on high-pressure steam. In this turbine the governing is effected by giving the low-pressure governor valve a lead over the high pressure, so that the full quantity of exhaust steam is always used before high-pressure steam is admitted.

In the Rateau mixed pressure type of turbine the pressure in the accumulator is allowed to act on a piston, which automatically cuts off the high-pressure steam supply, when there is an ample quantity of exhaust steam available to cope with the load, and automatically admits the high-pressure steam when this supply fails.

The electrical portion of the plant is, of course, identical with that of any standard high-pressure turbo-generator installation, and therefore does not in this connection call for any special mention. Perhaps the most interesting development is the use of the radial face commutator, which appears to have quite eliminated the old troubles due to vibration.

Heat Accumulator.—This is necessary in the very many cases where the supply of steam is intermittent, and it is used to act as a sort of heat flywheel; the principle will readily be grasped from the cross-section of an accumulator shown in Fig. 2. The steam passes through longitudinal tubes in the cylindrical shell, containing water, and escapes through small holes in these tubes, thus throwing the water into violent agitation, which by the introduction of suitable baffles produces a perfect circulation. When the quantity of steam entering the accumulator is

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in excess of the demand, the pressure rises, and the steam is condensed, the pressure falling and the steam re-evaporating, when the demand is in excess of the supply.

This accumulator is built under the Rateau patents, and although there are others on the market, it appears easily to hold the field. The exposed surface is very small compared with the quantity of water contained and the volume of steam handled, and thus only about 1 per cent. is lost in radiation.

The size is governed by the amount of steam available and the

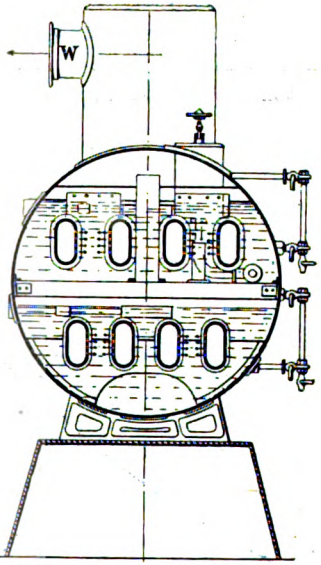

FIG. 2.—Rateau Water Type Heat Accumulator.

maximum length of the stop, and the range of pressure may be kept within very small limits, say from 2 to 2½ lbs.

The amount of exhaust steam available should be calculated from the indicator diagrams, and not from the duty of the boilers, since in all cases there is a loss of from 15 to 20 per cent., due to condensation in the engine and piping, and in some cases this loss is even much greater; it should be pointed out that this water of condensation is of no use in the turbine, as, although a certain amount of re-evaporation will take place, this is more than counterbalanced by the increased frictional losses. The dryness fraction of the steam coming from the accumulators is usually about 0·85, and the performance of the turbine will be improved if a steam separator is used.

Condensing Plant.—High vacuum is very necessary in all turbines, but especially in the type under discussion, since it is only under vacuum that it is possible to run them at all.

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Fig. 3 shows the increased percentage power gained for each inch of vacuum in a turbine working on steam at atmospheric pressure; the condensing plant is therefore of vital importance and must receive very careful consideration.

Water.—The quantity of water necessary for cooling purposes increases very rapidly with increase in temperature; consequently the water supply is of great importance.

Surface Condensers.—The great and practically only advantage of

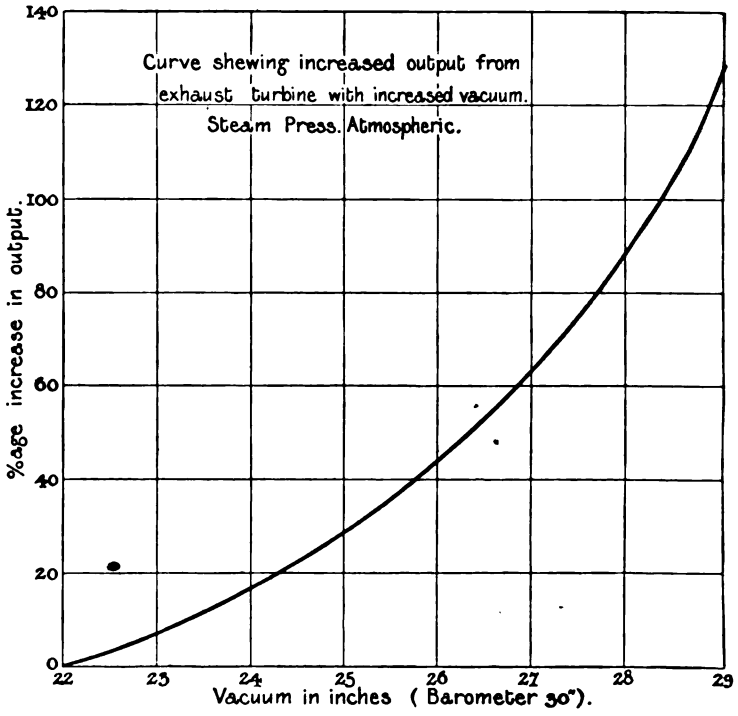

FIG. 3.

the surface condenser is, that the condensed steam may be used for boiler-feed purposes, and in some cases, where the water supply is very impure, its use is absolutely necessary; but there is no doubt that it has been used in many cases where it would have paid to spend a small amount on the purification of the boiler feed water and to use jet condensers.

Jet Condensers.—The various types of jet condensers are well known, but it will, no doubt, be interesting to give a short description of the latest arrival, which has practically come to the front in this country only within the last twelve months; this is the Leblanc multiple jet

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condenser, which has been developed by the Société Anonyme Westinghouse in France.

The principle will be readily grasped from Fig. 4, which shows the condenser partly in section and partly in elevation.

The steam is admitted at the top B, and meeting the injection water, which has a considerable velocity imparted to it in the nozzles C, is

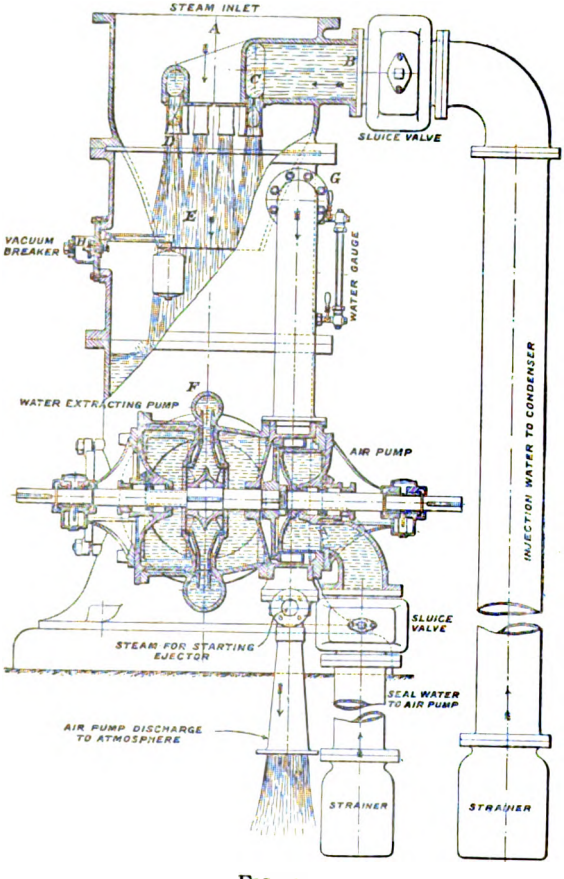

FIG. 4.

condensed, and, together with the air, is carried through the contracting cone D, there being a certain ejector action; the mixture then falls to the bottom of the condenser, and is extracted by a centrifugal pump. The air rises round the outside of the cone, and is removed by a rotary air pump of special construction, which is seen in Fig. 5. Water is forced to the centre of this pump by the pressure of the atmosphere,

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and entering the guide vanes with considerable velocity, which is further increased by the moving vanes T in the rotor, is sprayed by these vanes in such a manner as to entrap the air and pass it through

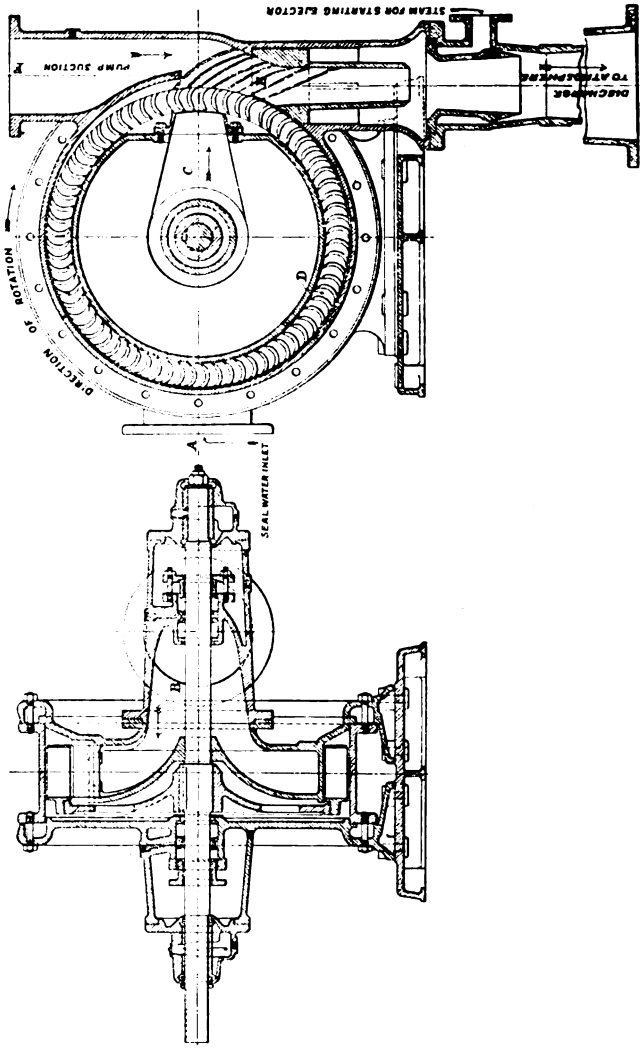

FIG. 5.

the cone C, where it is discharged against the atmosphere; both pumps are mounted on the same shaft, and are driven from the same motor. This dry-air pump is also used in connection with surface condensers.

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Apart from the question of efficiency, the most striking feature of this condenser is, that it is possible to instal a complete power plant in which reciprocating parts have no place.

Section 2.

We must now turn our attention to the possibilities of improving the economy of power stations where reciprocating condensing engines

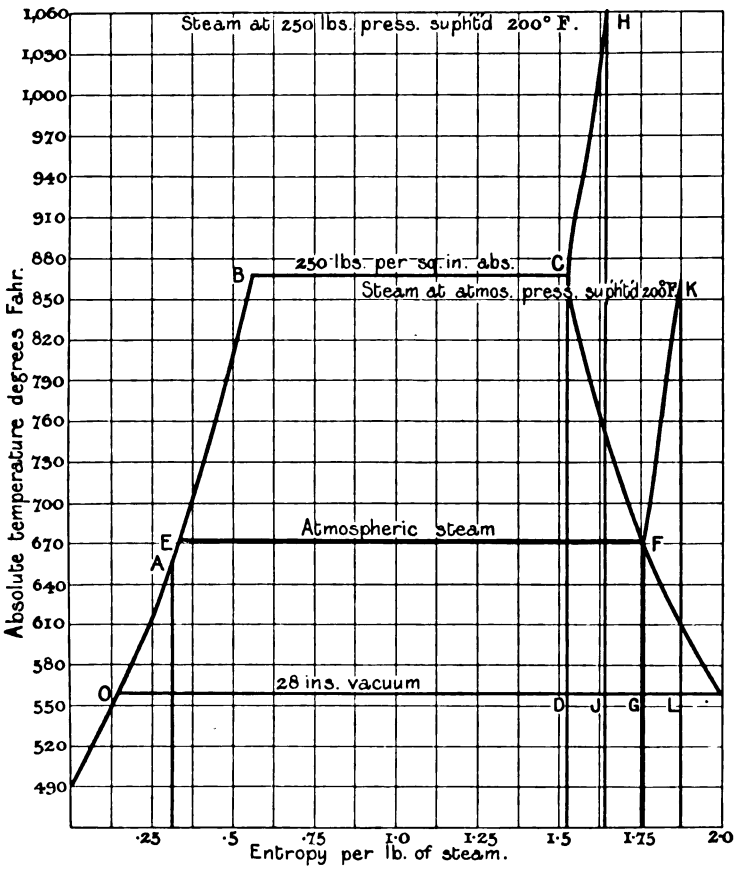

Fig. 6.

are already installed, and the statements made as to the efficiency of the low-pressure turbine will, of course, apply in general to Section 1.

In order to realise fully these possibilities, we must first get a clear idea of the great advantage to be derived from increasing the range of pressure through which any prime mover using steam works, provided

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that the energy in the steam is utilised efficiently at both the high- and low-pressure portions of the cycle.

To demonstrate this, let us take two cases, in both of which the feed water to the boilers is raised to 200° F. in an economiser, thus placing them on the same basis, and giving approximately the same boiler efficiencies:—

1. Steam generated at 250 lbs. per square inch absolute and expanded adiabatically down to 28 in. vacuum.
2. Steam generated at 15 lbs. per square inch absolute and expanded adiabatically down to 28 in. vacuum.

From entropy diagram, Fig. 6, it will be seen that although in case 1 only 5·8 per cent. more heat is added to the steam initially, 108 per cent. more heat is rendered available for work; and although in case 2 less heat is put into each pound of steam than in case 1, actually more heat per pound is turned into the condenser.

If we assume that the efficiency ratio, *i.e.*—

$$\frac{\text{energy given out at engine shaft}}{\text{energy theoretically available from steam}},$$

is the same in each case, the high-pressure plant will be about twice as efficient as the low-pressure, and, moreover, the boiler and condensing plant of the latter will be much more bulky and expensive.

By taking intermediate pressures, a curve similar to A, Fig. 7, is obtained, showing how the efficiency rises with increase of pressure. On the other hand, by keeping the initial pressure constant for cases 1 and 2 and varying the vacuum from, say, 22 to 28 in., curves B and C are obtained, showing the rise in efficiency with better vacuum. These curves show that the last inch or so of vacuum, when the initial steam pressure is high, are not nearly so important as when it is low.

Superheating.—The possible thermodynamic gain by the use of superheat is very small compared with the gain to be derived from increasing the pressure. This will be seen by taking two cases similar to the last, but with steam superheated 200° F.

We then have—

Steam at 250 lbs. absolute, superheated 200° F., and expanding adiabatically down to 28 in. vacuum.

Steam at 15 lbs. absolute, superheated 200° F., and expanding adiabatically down to 28 in. vacuum.

It will be seen that by adding 10 per cent. more heat in the form of superheat in both cases we get an increase of 14 per cent. and 18·5 per cent. respectively in the heat available. This shows that the theoretical gain due to superheat is very nearly independent of the pressure, and that the net gain for 200° F. is only from 4 to 8½ per cent. As a matter of fact the actual gain is, of course, considerably greater

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than this, owing to the reduced skin friction in the turbine and reduced condensation in the reciprocating engine.

Efficiency.—The available heat in the cycles considered cannot, of course, all be turned into work in the engine, but whereas in either a

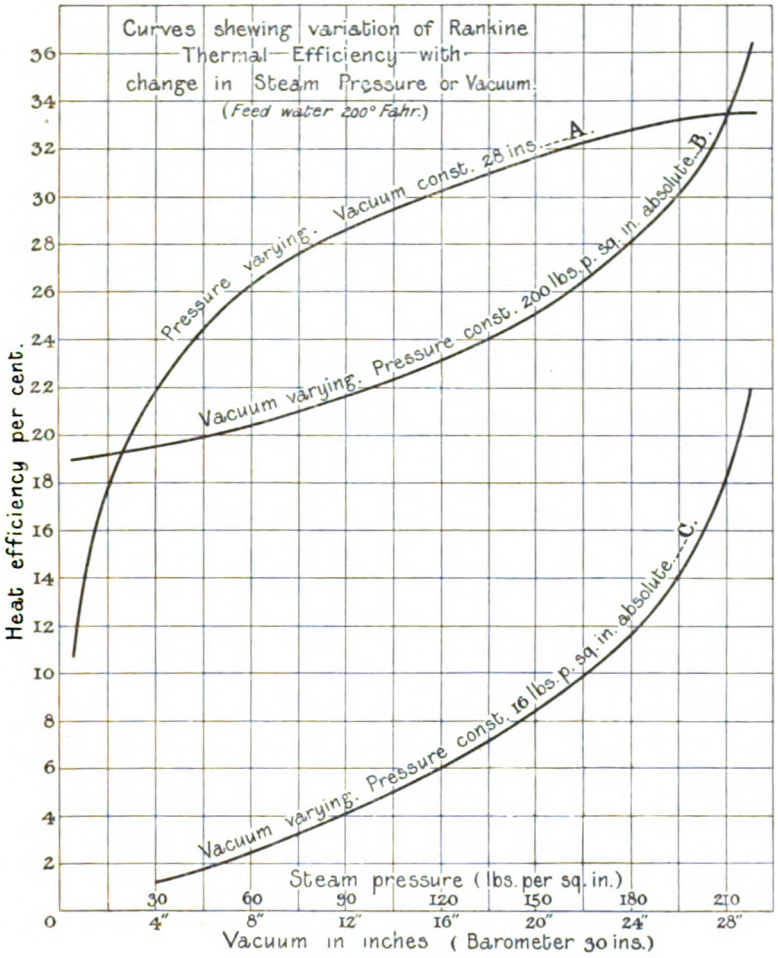
Curves shewing variation of Rankine Thermal Efficiency with change in Steam Pressure or Vacuum.
(Feed water 200° Fahr.)
Pressure varying. Vacuum const. 28 ins.---A.
Vacuum varying. Pressure const. 200 lbs. p. sq. in. absolute.---B.
Vacuum varying. Pressure const. 16 lbs. p. sq. in. absolute.---C.
Heat efficiency per cent.
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36
Steam pressure (lbs. per sq. in.)
30 60 90 120 150 180 210
Vacuum in inches (Barometer 30 ins.)
4" 8" 12" 16" 20" 24" 28"

FIG. 7.

turbine or reciprocating condensing engine working alone, only from 50 to 70 per cent. of the heat can be changed into work, by using the combination, from 70 to 80 per cent. can be realised. When it is considered that we gain not only this greatly increased mechanical efficiency, but also a greatly increased thermo-dynamic efficiency, the

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possibilities of the combination for reducing steam consumption will be evident.

Conditions under which it is advantageous or otherwise to put in

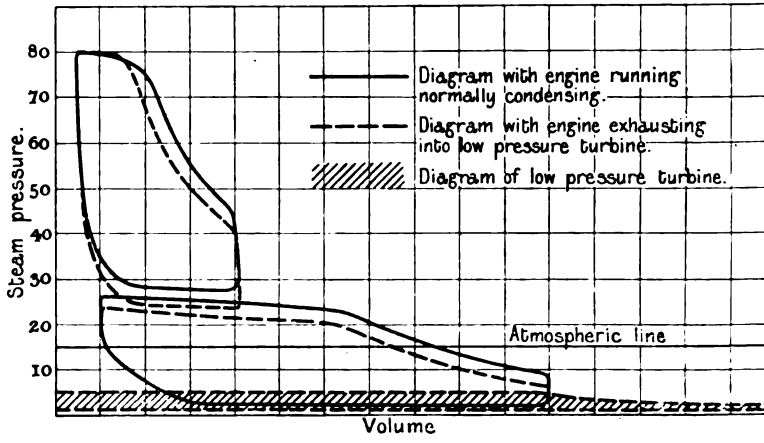

FIG. 8.

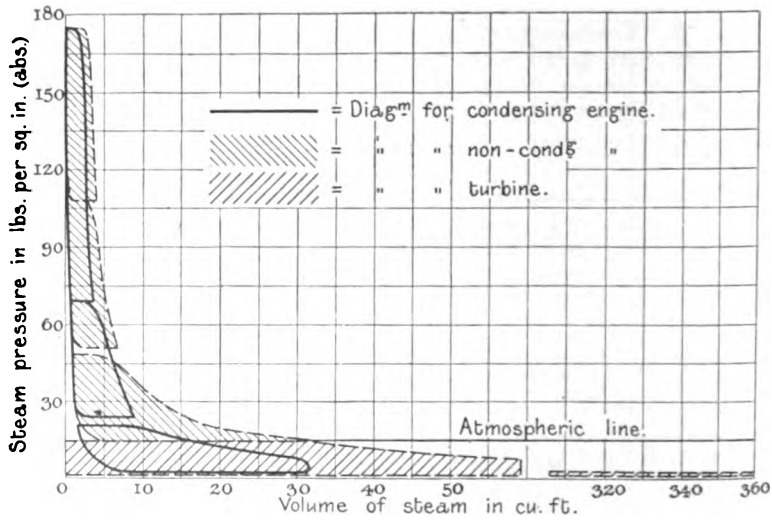

FIG. 9.

the Combined Plant.—The possibilities outlined above have already been proved in practice in marine work.

A word of warning is necessary, however. It must be distinctly understood that no advantage is to be gained by installing a low-

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pressure turbine if the only object aimed at is to decrease the steam consumption, keeping the output the same.

An advantageous change is only possible when, in addition to reducing steam consumption, an extension of the plant is contemplated. This will be clear when we consider the indicator diagram, Fig. 8. If the output remains constant, reduced steam consumption must necessarily mean earlier cut-off, and consequently more complete expansion of the steam in the engine itself (say from 10 in. to 16 in.). To expand the steam from 18 in. to 28 in. is all that is now left for the turbine to do, and obviously this would give very little output, and would be an insignificant return for the capital cost incurred. If, on the other hand, the intention is to put down an additional unit of nearly equal, or larger, capacity than the existing one, an excellent opportunity is afforded for the use of the low-pressure turbine.

We have considered the heat diagram of the combination, and it is interesting to compare this with the indicator diagram. An actual indicator diagram plotted from the indicator cards of a triple expansion engine is shown in Fig 9. If the full output is to be maintained non-condensing, the area of the diagram must still be the same, and the cut-off will be increased from, say, $\frac{1}{4}$ to $\frac{3}{4}$ stroke in the high-pressure cylinder, the cut-off in the other cylinder being also increased. If the diagram be now completed to the full vacuum of 28 in., it shows very well the work done in the turbine, and illustrates how absurdly large the engine cylinders would need to be to give the same result.

Some actual results will be found in the curves at the end of the paper, but I think the figures cited below will bring out even more clearly the results to be expected from the combination.

A 750-k.w. (1,080 B.H.P.) triple-expansion high-speed steam engine, by a well-known maker, gives steam consumptions as follows, which I think all will agree are quite reasonable :—

	Saturated Steam (1,080 B.H.P.).	
	Condensing Engine.	Non-condensing Engine.
Steam pressure	150 lbs. per sq. in.	150 lbs. per sq. in.
Vacuum	26 in.	Atmosphere
Steam consumption at full load	14·5 lbs. per B.H.P.	19·5 lbs. per B.H.P.
Heat available in steam in expanding	285 B.Th.U.	173 B.Th.U.
Corresponding efficiency of engine as compared with Rankine cycle ...	62 per cent.	75 per cent.

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This engine is therefore 13 per cent. more efficient when running non-condensing than when running on a vacuum of 26 in.

Now, each lb. of steam exhausted from the non-condensing

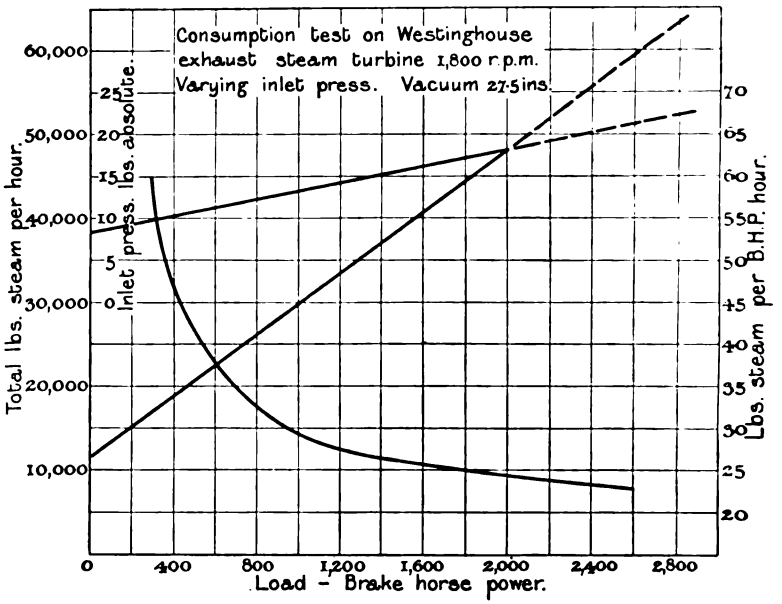

FIG. 10.

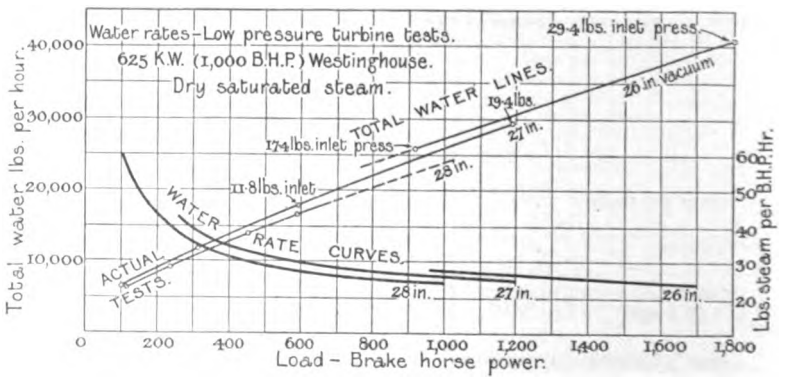

FIG. 11.

engine, if expanded down to 28 in. vacuum in a low-pressure turbine, will give out a further 144 B.Th.U. of heat, and the turbines will utilise this quite as efficiently as the engine has already used the heat in the

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high-pressure steam. Let us suppose, however, that there is a loss of 10 per cent. in various ways between the engine and turbine, and take the efficiency of the latter as 65 per cent. instead of 75 per cent. The actual consumption of the turbine will then be 27·4 lbs. per B.H.P.-hour (corresponding to about 40 lbs. per kilowatt-hour, which is a figure easily obtainable in practice).

This means that after the 21,000 lbs. (*i.e.*, 19·5 × 1,080) of steam have passed through the engine, giving 1,080 B.H.P., they give another 770 B.H.P. in the turbine—the overall consumption is therefore $\frac{21{,}000}{1{,}080 + 770} = 11{\cdot}35$ lbs. per B.H.P.-hour (16·5 lbs. per kilowatt-hour).

Clearly, then, in this case, if instead of extending by putting down another engine, a low-pressure turbine is installed, the steam consumption at full load will be reduced 3·15 lbs. per B.H.P.-hour—*i.e.*, 4·6 lbs. per kilowatt-hour, *nearly 22 per cent.*

Taking similar figures for superheated steam :—

	Condensing Engine.	Non-condensing Engine.
Steam pressure	150 lbs. per sq. in.	150 lbs. per sq. in.
Superheat	120° F.	120° F.
Vacuum	26 in.	Atmosphere
Steam consumption at full load	12·5 lbs. per B.H.P.-hour	16·8 lbs. per B.H.P.-hour
Heat available from steam in expanding	307 B.Th.U.	186 B.Th.U.
Corresponding efficiency of engine as compared with Rankine cycle ...	66 per cent.	81 per cent.

In this case, although the engine is 15 per cent. more efficient non-condensing than condensing, the percentage overall saving is less than before, being only 19 per cent.; this is because the output of the turbine is only 710 B.H.P., as compared with 770 B.H.P. in the previous case. The same thing occurs if, instead of superheating, the steam pressure is raised, as will be seen from the table on page 766.

This table shows that increase of steam pressure largely reduces the steam consumption of the engine, whereas it actually increases that of the turbine—*e.g.*, raising the pressure from 80 to 200 lbs. per square inch reduces the consumption of the engine, and increases that of the turbine by 30 per cent. and 5 per cent. respectively; consequently, if a low-pressure turbine, designed to run on atmospheric pressure, is

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used with an engine working under very good steam conditions, its output will only be from 60 to 70 per cent. of that of the engine.

Probably in such cases the best method of increasing the output of the turbine is to arrange the valve gear so that the engine will give its full output when working against a back pressure—*e.g.*, if the engine in column 5 works against a back pressure of 10 lbs., its steam consumption will be increased to 21·5 lbs., and the corresponding consumption of the turbine will be 22·2 lbs.; the output of the latter is therefore 1,045 B.H.P., which is nearly equal to that of the engine, and the overall consumption per B.H.P.-hour is 11·0 lbs., a reduction of 17 per cent. (3·3 lbs. per kilowatt-hour) from the figure got with the

1,080-B.H.P. NON-CONDENSING ENGINE, SATURATED STEAM.

Exhausting into Low-pressure Steam Turbine.

Steam pressure, lbs. per sq. in.... ...	80	100	130	160	200
Consumption of Engine in lbs. per B.H.P.	26·0	23·6	21·0	19·2	18·0
Total steam per hour, 1,080 B.H.P. ...	28,000	25,500	22,700	20,800	19,500
Consumption of turbine, lbs. per B.H.P.	25·8	26·0	26·7	26·9	27·0
Output of turbine in B.H.P.	1,080	935	850	775	722

engine running normally condensing. This is much more satisfactory than increasing the output by putting down a mixed pressure turbine.

The figures cited above are all given on the assumption of an efficiency ratio of 65 per cent. in the turbine, the vacuum in all cases being 28 in.; but as a matter of fact this figure can be improved upon, and it is possible to get the same results in practice, with a vacuum of from 27 to 27½ in., depending upon the size of the unit.

The economy improves, of course, with the size of the set, and, in fact, where units of 5,000 k.w. are under consideration—*i.e.*, a combination of 10,000-k.w. capacity, there is no reason to doubt that consumptions of 11 lbs. per kilowatt-hour can be realised, if the steam conditions are good.

Concluding Remarks.—It may be taken in general that the cost of a low-pressure plant, as described in Section 1, with accumulator, is certainly not greater than that of a high-pressure plant, with boilers;

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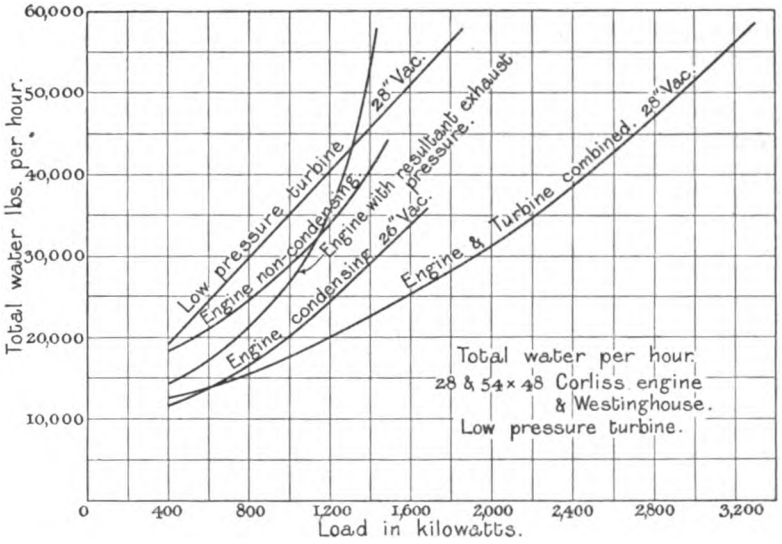

FIG. 12.

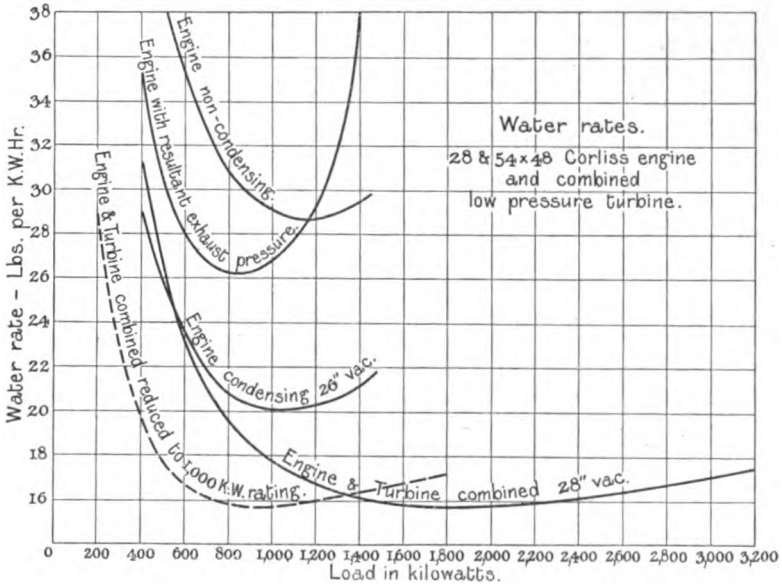

FIG. 13.

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and, in cases where the accumulator can be dispensed with, the cost for installations above 200-k.w. capacity is decidedly less.

In Section 2, for outputs above 500 k.w., the cost will be much less than the installation of reciprocating sets—when large outputs are reached it is only about one-half. The turbine itself will be approximately the same price as a high-pressure turbine, but each case must carefully be considered on its merits, as local conditions vary very considerably.

It is impossible in this paper to treat the question of costs in detail, but it is hoped that sufficient has been said to influence those not yet familiar with the subject to apply to the manufacturers for information concerning cases coming under their notice, in which the installation of low-pressure plant appears to be desirable.

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THE RADIO-TELEGRAPHIC STATION AT CULLERCOATS.

By AAGE. S. M. SÖRENSEN.

(*Paper received from the* NEWCASTLE LOCAL SECTION, *May* 1, 1909.)

It is my intention in this paper to give a description of the erection, installation, and general working of the radio-telegraphic station at Cullercoats, and as radio-telegraphy forms a special branch of electro-technology it will presumably not be out of place to start with a few notes on the principles of the production of electric oscillations and electro-magnetic waves.

You will doubtless be aware that the discharge of a condenser becomes oscillatory when it takes place through a self-induction. Maxwell explained theoretically how the electric oscillations in such a circuit, by creating alternate electric strain and magnetic flux in the surrounding dielectric medium, would create an electro-magnetic wave propagated through space.

It will, however, be seen that if the condenser after charging is connected to a helix the energy will soon be dissipated, and nothing further will happen until the condenser is recharged. But the closed circuit consisting of an ordinary condenser, such as a Leyden jar and a self-induction helix, is a very bad radiator. It was therefore not until Hertz applied the open-circuit oscillator and the spark that electro-magnetic waves were actually generated and their existence practically proved. The Hertz oscillator consisted of two metal rods with metal balls at one end, the balls being placed near together, and forming a spark-gap between them, while at the other ends metal plates were fixed to the rods, these plates forming the condenser. The sparking balls are connected to the secondary of an induction coil from which the condenser is charged, and when a certain potential is reached the discharge takes place through the spark-gap. The circuit is thereby completed, oscillations are set up in the circuit, and a train of waves radiated. By means of some similar circuits containing a very small and adjustable spark-gap, Hertz succeeded in detecting the existence of the waves at some distance from the apparatus.

A much more powerful radiator is obtained by using long vertical wires, the so-called antennæ, on one side of the spark-gap, and connecting the other side to earth. The use of such aerial wires was originated by Popoff in research on atmospheric electricity.

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A sensitive apparatus for detecting electric oscillations—the coherer—was obtained by Branly, who discovered that an imperfect contact alters its resistance considerably under the influence of electric oscillations.

So far the work on this subject was confined to scientific research. But the time had then come for practical application, and Signor Marconi, by inserting a telegraph key in the primary of the inductorium and connecting a Morse-inker with the coherer in the receiver, succeeded in controlling the impulses sent out and received in the shape of Morse code signals, and was thus the first to establish radio-telegraphic communication. From that time improvements in radio-telegraphy have progressed quickly.

It will be understood that the oscillations created by directly exciting a plain antennar circuit (open circuit) must die out rapidly, the energy being quickly dissipated by the radiation. The oscillations are strongly damped, and comparatively long inactive intervals follow each train of waves.

A great improvement was made by the introduction of the closed circuit, inductively or directly exciting the open radiative circuit, known as the coupled system. To obtain the maximum effect of oscillations in one circuit on another the two circuits must be in electrical resonance, *i.e.*, have the same natural frequency. The frequency of oscillations in a circuit of self-induction L and capacity C is—

$$n = \frac{1}{2\pi\sqrt{L\,C}}.$$

It is, of course, not only the circuits in a coupled system that have to be in resonance, but likewise the sender and receiver, which must be "tuned" to one another, as it is more commonly termed. The exactness with which such tuning can be effected depends on the damping. The smaller the damping, the sharper is the tuning. The use of tuned circuits was originated in Germany by Professor Braun, and in this country by Sir Oliver Lodge, and is now used in practically all wireless systems.

The receiver has been further improved by the invention of better detectors, such as the magnetic, electrolytic, and thermo-detectors, and crystal rectifiers. Starting from such technical differences in design of apparatus and detectors used, the numerous different spark systems have been developed, but in principle they are all the same. Such systems are, for instance, the Marconi, Telefunken, De Forest, Lodge, Muirhead, and Fessenden systems.

The description of the spark-system installation at Cullercoats will, with a few additional remarks, give a good idea of the construction and working of a spark-set of any type.

The building of the Cullercoats radio-telegraphic station was started in February, 1906, and the mast and house completed about June, 1906.

The mast is a lattice-build pole which was completely constructed to its full length lying on the ground (Fig. 1). After fixing the upper ends

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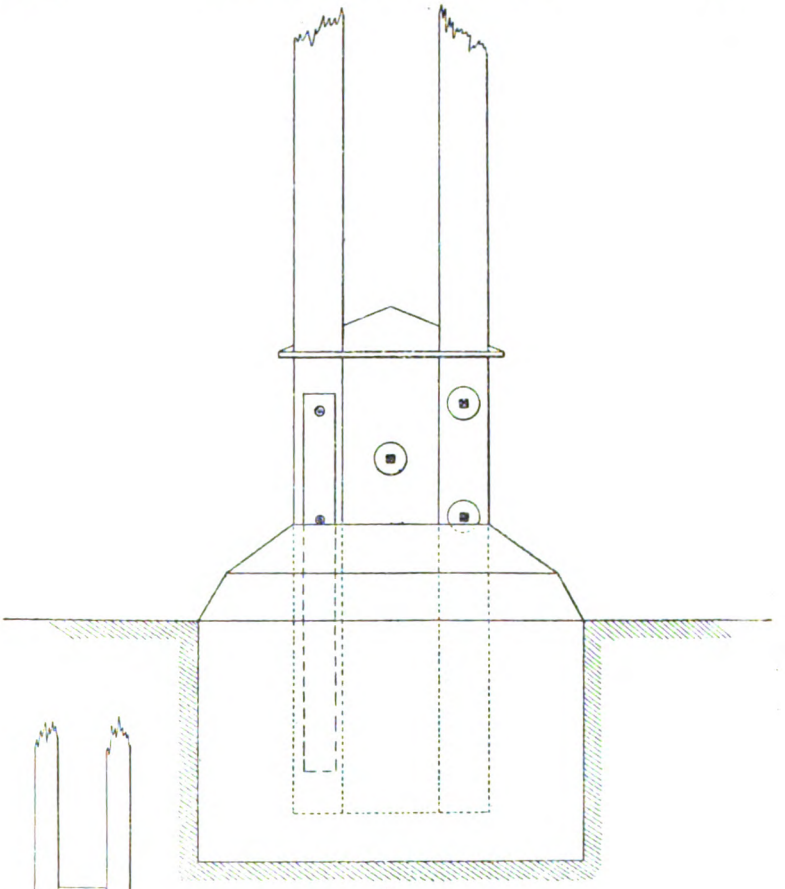

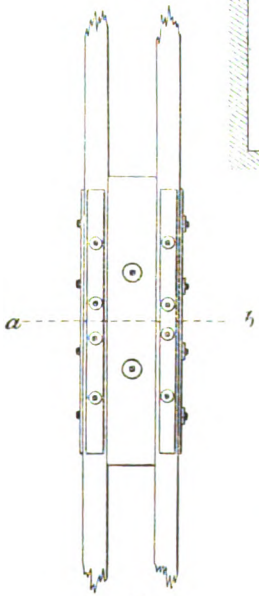

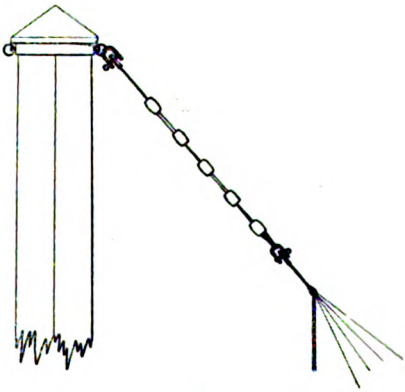

FIG. 1.—Details of Mast.

A. Foundations.
B. Joint with iron fishplates.
C. Cross-section of joint.
D. Top of mast with detail of antennæ suspension and top insulators.

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of the guys to the mast, it was lifted bodily into position by means of a derrick crane. The illustrations show different stages of this process. The house, which was in a temporary position while the mast was being hoisted, was afterwards shifted to its final position. The erection of house and mast having been completed, a set of spark apparatus was installed. This first installation has, however, been greatly altered since, and is therefore not described here.

The mast serves to support the antennæ, which originally took the form of an inverted fan, consisting of 8 wires connected at the top

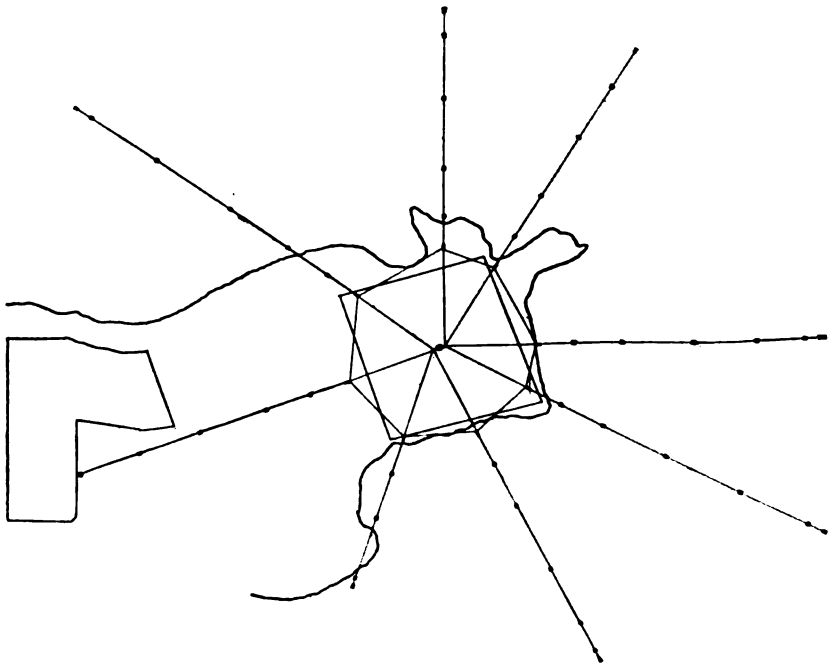

FIG. 2.—Plane of Antennæ and Antennæ-stays, showing position of Anchors on the Foreshore.

and about 60 ft. from the ground, spread at equal distances between two smaller masts, 150 ft. apart. The wires were connected to the inlet insulators on the roof, 4 wires meeting at each of the 2 inlets.

The present antennæ are made in the umbrella shape (Fig. 2). Eight wires are suspended between the top of the pole and 8 iron posts, arranged on the rocks and on land at nearly equal distances apart, in a circle round the pole. The upper 160 ft. of each wire forms part of the antennæ, and is separated by a long insulator of hard rubber from the rest of the wire, which only serves as a stay. The lower ends of the 8 antennæ wires are connected by an octagonal boundary wire.

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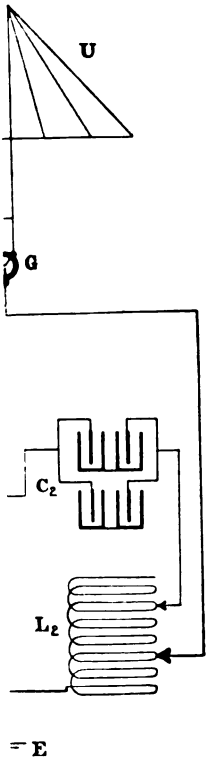

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At the top of the mast 4 wires come together on each side, and are there joined to 2 copper cables, which run down to the leading-in insulators on the roof. The two half parts are suspended from the top of the mast by means of a series of porcelain insulators, and similar insulators are used to cut the guys into short lengths. The insulators are constructed so that the wires are looped into each other through the insulators, and in case an insulator breaks the wires will remain in position. The antennæ are made of 7-stranded, silicium-bronze wire, strand No. 20.

The earth connection consists of 70 copper wires of about 2 mm. diameter, laid about 6 in. under the surface, and spreading from the centre of the cabin in all directions like the spokes of a wheel. The average length of the earth wires is 130 ft. The interior of the cabin is divided into four rooms, of which three are occupied by the spark apparatus.

The engine-room contains a motor-generator and the necessary regulating apparatus. The town supply at 480 volts is used. The speed of the motor can be regulated by field resistance from 1,800 to 2,400 revs. per minute, and the motor started automatically by a motor starter of the "Igranic" type, which is controlled from the operating-room. The dynamo is a single-phase alternator, which gives 90 to 120 cycles according to the number of revolutions. By field regulation the voltage can be altered from 300 to 600 volts. To protect the dynamo from high-frequency induction, the cables pass through choking coils with spark arresters before they enter the operating-room, where the telegraph key and a variable reactance are inserted in the circuit, which is completed in the third room—the spark-room—through the primary winding of a dry transformer. The secondary of the transformer is connected to the spark-gap, across which is shunted a battery of Leyden jars and a self-induction helix, forming the closed oscillating circuit; the antennæ and the earth connections are taken off from two points of the same helix, thus forming a so-called galvanic or direct coupling. As the fundamental wave-length of the antennæ (*i.e.*, the wave-length obtained when the antennæ are connected direct to earth through the spark-gap) is 800 metres, and the normal working wave is 600 metres, the antennæ are "shortened" by an inserted small battery of Leyden jars. Over these jars the antennæ are "interrupted" by an anchor spark-gap, which ordinarily leaves the antennæ disconnected from the sender, but during sending is bridged across by a spark.

As already mentioned, the operating-room contains the telegraph key, which is installed on the table beside the receiver, and also the ammeter and voltmeter for the power circuit.

A branch of the antennæ comes into the operating-room to a switch, by which it can be joined through a self-inductance and a condenser to earth. This apparatus forms the receiving circuit, which can be tuned by varying the capacity and the self-inductance (Fig. 3). The condenser consists of a set of semicircular plates, which can be turned in and out in the spaces between a set of similar fixed plates, whereby the capacity

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can be altered. The helix has 100 turns of thick insulated copper wire about 1 mm. in diameter, and terminals at different places, arranged so that a number of turns in steps of five can be branched off. If self-inductance and capacity are arranged in series with the antennæ and earth, the receiver can be tuned to wave-lengths from 300 to 1,000 metres, and when the condenser is shunted across the inductance, to wave-lengths of between 800 and 2,500 metres.

Inductively coupled to the tuning helix is another coil, the ends of which are connected to the detector, in this case a De Forest electrolytic cell, by means of which the received energy is transformed into audible signals composed of long and short sounds in a telephone.

Ordinarily the operator on duty is constantly listening in this telephone, and on 600 metres wave-length. A ship intending to communicate with the station will send a call-signal with the names (in code) of the called and the calling station. To reply, the operator breaks the antennæ switch, which in its other position closes the circuit to the control relay of the motor starter, the motor starts, and in 10 seconds the transmitter is ready for making the reply. When this has been done, the antennæ are switched over again, the motor stops, and receiving conditions are immediately re-established. In this way the communication is kept up between ship and shore station as long as working requires.

It will be readily understood that the described arrangements could be modified in several ways. In short-distance work, for instance, a spark coil might be employed instead of motor-generator and transformer. Further, the sender could be arranged with a single open circuit or with inductive, instead of galvanic coupling, and likewise the receiver, where also special hooking devices may be used for the various forms of detectors. But the systems are all able to intercommunicate, and a common feature in all of them is that the waves are damped and interrupted.

It was mentioned above that the maximum effect from a certain sender had a corresponding "tuning" in the receiver, but the effect can be obtained on both sides of the maximum over a certain range; the smaller this is, the sharper the tuning is said to be, and the degree of sharpness depends on the damping.

A curve giving the relation between amplitude and wave-length is called a "resonance curve," and is for damped oscillations a rather flat curve, while undamped oscillations will give a curve with a high, sharply marked peak. This can be proved theoretically, and some of the obvious advantages which could be obtained by applying undamped oscillations for radio-telegraphy were described by several writers long before it had been discovered how to generate such oscillations, and naturally several workers were trying to solve the problem. Duddell was the first to succeed in this. When working on research on the speaking arc, he noticed that an electric arc burning between two solid carbons in atmospheric air, when shunted by capacity and self-induction of suitable values, would give out a musical note. The

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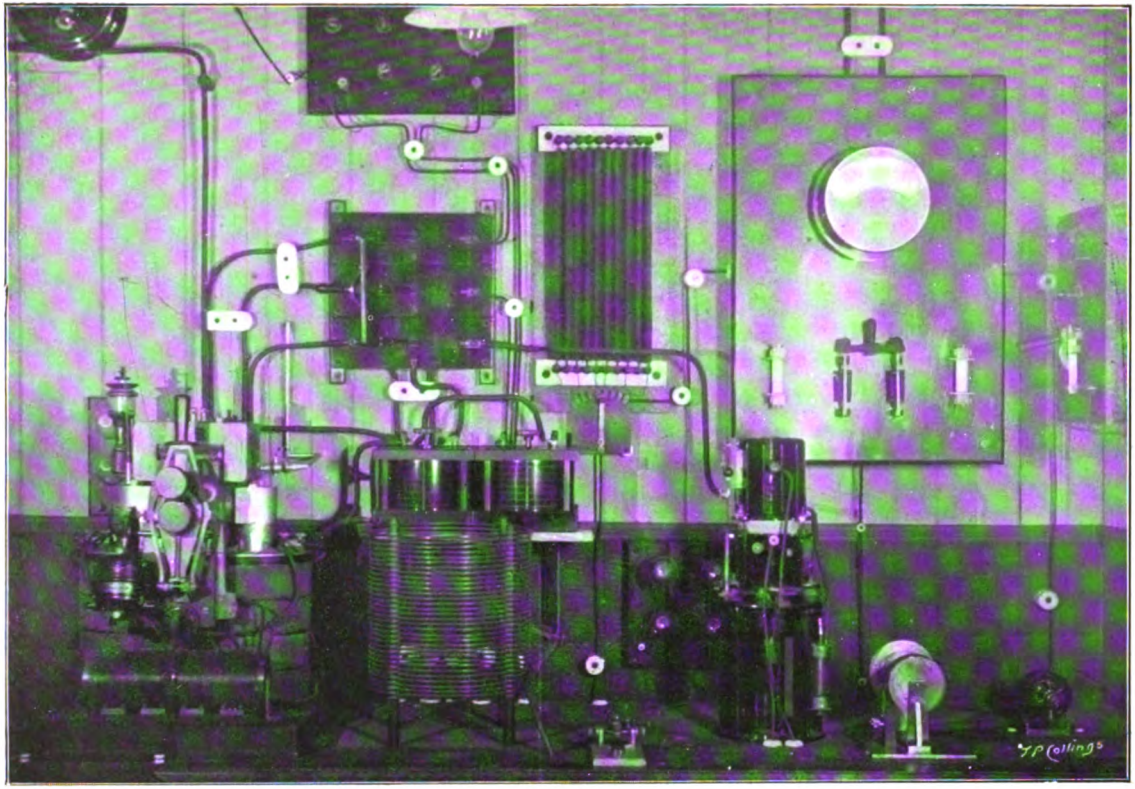

FIG. 5.

3 K.W. Poulsen Generator. Variable Condensers. Variable Self-inductance ½ K.W. Poulsen Generator. Switchboard Key

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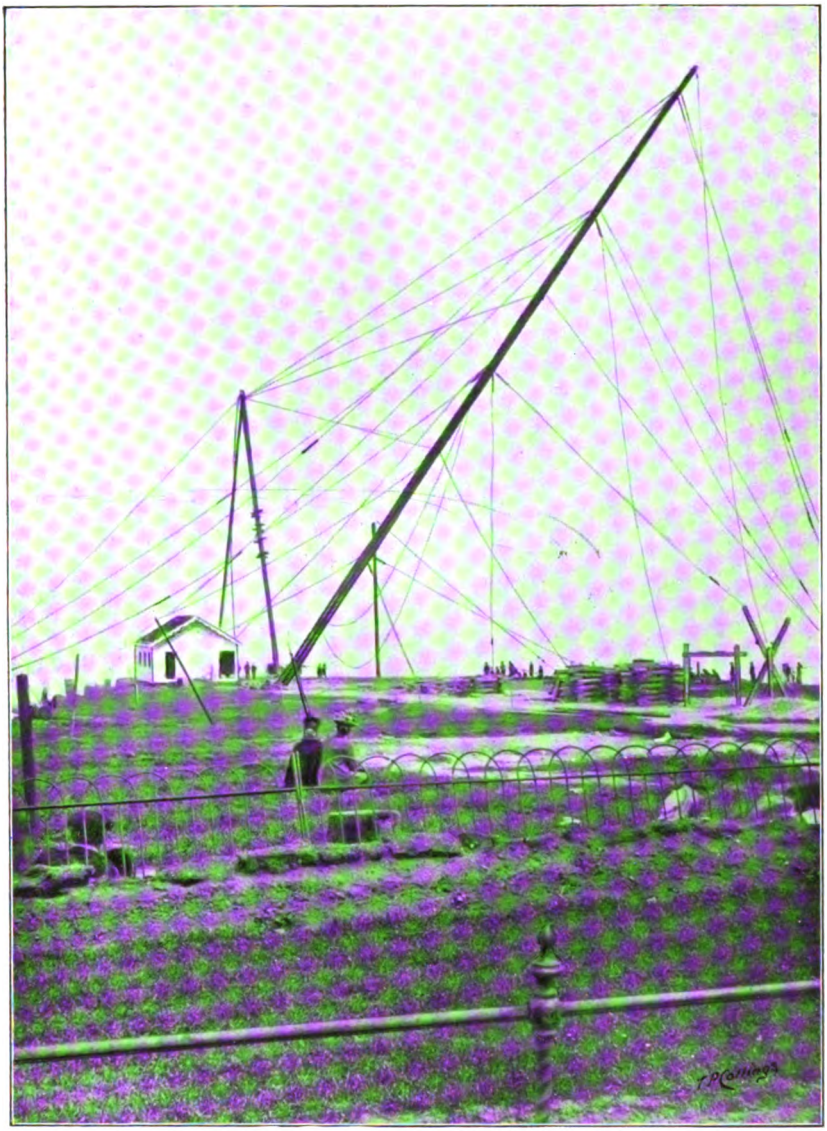

FIG. 6.—Erection of Mast, 1906.

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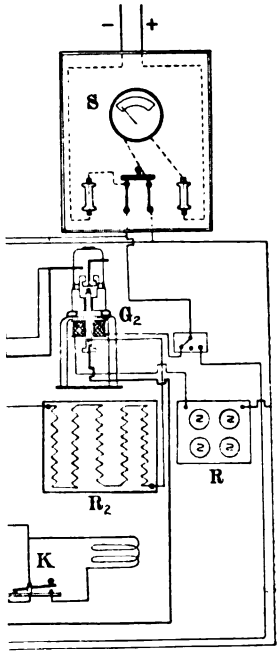

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frequency was determined by that natural to the circuit, and notes of frequencies between 2,000 and 10,000 were obtained. Higher frequencies up to 40,000 were reached in later researches, but the energy obtained was very small, and the frequencies lower than those applicable to radio-telegraphy; until the Danish engineer, Valdemar Poulsen, discovered that an arc between carbon-copper electrodes, placed in an atmosphere of or containing hydrogen gas and in a magnetic field, would give powerful oscillations up to frequencies of about one million and a half. The fact can be explained by the steepness of the characteristic curve of an electric arc, this steepness being increased by placing the arc in hydrogen, but a full outline of the principles involved would go beyond the scope of this paper.

Immediately after his discovery Mr. Poulsen started experiments on radio-telegraphy, and in a short time the Poulsen system was developed so far that the construction of complete apparatus for practical use could be started (Fig. 4). In November, 1906, a receiver of the Poulsen type was installed at the Cullercoats station, and at the first test signals were received from the Danish stations, Lyngby and Esbjerg, over distances of about 400 and 600 miles respectively. Early in 1907 an experimental arc was set up in Cullercoats, and very satisfactory results were obtained, considering the energy and the small antennæ then used. In 1908 the antennæ at Lyngby and Cullercoats were extended, and the stations equipped with generators of up-to-date design, and since then perfect working has been obtained at all times between the three stations.

It was mentioned above that the cabin at Cullercoats had four rooms, and the installations in three of them have been described. The fourth is occupied by the complete Poulsen installation, consisting of the two essential parts, sender and receiver.

The sender comprises the generator, the oscillatory circuit with capacity and self-induction, antennæ, and earth. As the oscillatory tension between the condenser plates is much smaller in a Poulsen arc sender than in a spark sender, it is possible to use condensers with air or oil dielectric of the design mentioned above, one advantage of which is that the capacity of the sender is readily altered, and as the distance between the plates only needs to be a few millimetres, the condensers occupy considerably less room than a battery of Leyden jars. The sending circuit or circuits can of course be arranged in exactly similar hooking devices to those of a spark sender, the arc taking the place of the spark-gap.

The generator is built in the following way: On an iron footplate are mounted two vertical iron cores, round which the magnetic field coils are placed. Above the coils an air-tight double-walled box is placed between the cores, and horizontal pole-pieces pass through the box on each side, an air space being left between them. The arc electrodes are passed through the end walls of the box, but are insulated from it, and are placed so that the arc is burning between the magnet poles. The copper electrode is in a fixed position, while the

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carbon holder can be moved to and fro by a screw for adjusting the arc length, rotated by a small motor through a wormgear. Outside the box the electrodes end in metallic plates with radiators for air cooling. From a sight-feeder (such as is used for oil in gas engines) methylated spirit is dropped into the arc, and by its decomposition generates the necessary hydrogen atmosphere.

The direct-current supply passes from the switch through a variable resistance, the magnetic field windings, and two air-cored choking coils, to prevent oscillations in the mains, to the arc electrodes.

The signalling is effected by letting the telegraph key short-circuit a part of the self-induction in the circuit, so that the arc is oscillating during the whole period of working, but two different waves are radiated, corresponding to marking and spacing.

It will be understood that as long as the key is pressed the transmitter generates a persistent train of constant oscillations, and consequently nothing would be heard in an ordinary receiver for audible signals. To produce sound it is necessary to cut the oscillations up in groups, occurring with a frequency which can be heard. So far this cutting up could be effected in the sender or the receiver at will.

By the "ticker," a very ingenious arrangement of Mr. Poulsen's, it is possible to employ this method advantageously in the receiver.

The Poulsen "ticker-telephone" receiver consists of a primary circuit (the ordinary antennæ-earth circuit, with necessary self-inductance and capacity for tuning), which is in inductive and extremely loose coupling with a secondary closed circuit, composed of self-inductance and capacity. Across the secondary condenser is placed through an intermittent contact (the "ticker") a condenser of large capacity (in comparison with the condenser in the circuit), and across this condenser is placed a telephone.

The action is as follows: If the "ticker" contact is broken the secondary circuit is quite free—that is to say, no energy is taken from the circuit, and if set in oscillation from a sender through the primary, the secondary circuit will accumulate energy by integrating the impulses; after a certain time the ticker-contact is closed, the circuits thrown out of resonance, and the secondary gives up the energy to the "block-condenser," which again discharges through the telephone; then the "ticker" closes again, and the process is repeated as long as energy is forthcoming from the sender and of the proper frequency. In this way the signal is marked in the telephone by a ticking noise, from which the apparatus is named.

It will be seen that this method allows a considerable amount of energy to be given off in the receiver at one time, although only oscillations of very small amplitude are created in the sender, while at the same time it requires and makes use of the sharpness of tuning obtained by undamped waves.

Detectors can be used without the "ticker" for printing arrangements. A specially sensitive type is the photographic printer, in which the feeble direct current obtained from the detector is passed through the

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fine wire in an Edelmann thread galvanometer. The wire moves in front of a slot, and through a microscope the slot is photographed, with the moving shadow of the wire, on a strip of sensitive paper. As the mass of the wire is extremely small the speed is nearly unlimited, as long as energy enough is obtained to give a visible movement. In this way messages have been received in Lyngby from Esbjerg at a rate of 300 words a minute, and at Cullercoats from Lyngby up to 100 words a minute.

Before concluding it should be mentioned that another important application of the undamped waves is to the science of radio-telephony. If a microphone is inserted in the sender the energy radiated can be varied in accordance with the tones of the voice, and by using a quantitative detector in the receiver combined with a telephone, the varying impressions will reproduce the voice. In this way it has been possible to transmit sound as far as between Berlin and Copenhagen, a distance of 260 miles, mostly over land.

A comparison between the arc and spark systems will certainly show the advantage of the arc system, which is bound in time to supersede the other method.

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Proceedings of the Thirty-seventh Annual General Meeting of the Institution of Electrical Engineers, held in the Rooms of the Royal Society of Arts, John Street, Adelphi, W.C., on Thursday, May 20, 1909 — Mr. W. M. MORDEY, President, in the chair.

The minutes of the Ordinary General Meeting held on May 13, 1909, were taken as read and confirmed.

The following list of transfers was announced as having been approved by the Council :—

TRANSFERS.

From the class of Associates to that of Associate Members :—

James William Burr.

From the class of Students to that of Associate Members :—

William Höjel Charters Coates.

Messrs. C. W. Fourniss and H. W. Irvine were appointed scrutineers of the ballot for the election of new members, and, at the end of the meeting, the following were declared to have been duly elected :—

ELECTIONS.

As Members.

Philip Denis Ionides.
Arthur Grotjan Marshall.
Walter Ambrose Pearson.
Wilfrid L. Spence.

As Associate Members.

Robert Douglas Archibald.
Charles Beech.
William Henry Brownjohn.
Bernard E. Bumpus.
Walter Edward Butcher.
Edward Lionel Castle.
Hugh Samuel Davidson.
Thomas Hubert Dennis.
James Dubbin.
John Lloyd Duus.
Alfred Walker Empson.
Maurice FitzGerald.
Joseph Augustine Forde.
Albert George Fox.
James Graham.
Arthur Emanuel Harrison.

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As Associate Members—continued.

William Vernon Haslam.
William Hockley.
William Jamieson.
Ernest Lefeaux.
Ernest George Lunn.
Clifford Edward May.
Thomas May.
Geo. Clement Milnes.
Einar Myhre.
Richard Edward Parnham.
Fred. William Peasnell.
Albert Edward A. Ridgway.
Percy Malcolm Robinson.
John Aitken Shaw.
Walter Tom Smith.
Henry J. F. Stewart.
Rupert Stockbridge.
Tom Percival Strickland.
Charles William Thompson.
James Stuart Thomson.
Tom Ellery Turner.
Horace Septimus Walker.
William Robert Warren.
Hugh Lawrance Williams, B.A.
Geo. Macdonald Wise.

As Associates.

William Murray.
Robert Robertson.
Herbert Charles Stoddart.
Harvey Richard Todman.

As Students.

Herbert Maxwell Browne.
William Kenneth Burke.
Charles Melsome-Smith.
Nanigopal Mukerjee.
Reginald Henry Rinaldi.
Acton Edward Sapey.
Walter Howard Shaw.
William Herbert Walton.
Trevor Montfort Wheeler.
Edgar Whitehouse.

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REPORT OF THE COUNCIL FOR PRESENTATION TO THE ANNUAL GENERAL MEETING OF MAY 20, 1909.

At this, the thirty-seventh Annual General Meeting of the Institution of Electrical Engineers, the Council present to the Members their Report for the Session 1908–9.

Growth of the Institution.

Since the date of the last Annual General Meeting, 421 proposals for election have been considered, and there have been elected 17 Members, 167 Associate Members, 17 Associates, and 206 Students.

To the class of Members there have been transferred 37 Associate Members and 8 Associates, to the class of Associate Members there have been transferred 26 Associates and 116 Students, and to the class of Associates there has been transferred 1 Student.

The change in the List of Members during the past twelve months is shown in the following table :—

	1908.	1909.
Honorary Members	5	7
Members	1,093	1,142
Associate Members	2,182	2,387
Associates	1,136	1,042
Students	1,543	1,432
Foreign Members	109	107
Total	6,068	6,117

During the Session under review, the Council have elected as Honorary Members, Mr. Oliver Heaviside, F.R.S., and the Hon. Charles A. Parsons, C.B., F.R.S.

Honours have been conferred upon several members of the Institution. Sir Henry H. Cunynghame has been created a Knight Commander of the Order of the Bath, and Knighthoods have been conferred on Sir Robert Hadfield (who has also been elected a Fellow of the Royal Society), and Professor Sir Joseph John Thomson, M.A., F.R.S.

Members Deceased.

It is with deep regret that the Council have to record the death, on November 9, 1908, of Professor W. E. Ayrton, F.R.S., who held the

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office of President in 1892, and at all times took an active part in the affairs of the Institution, with which he had been connected since 1872.

Other well-known members who have died during the last twelve months are The Rt. Hon. Lord Blythswood, F.R.S., Mr. E. J. Bristow (Honorary Solicitor), Monsieur Mascart (Honorary Member), Herr Emil Naglo (Member since 1872), Mr. C. H. Reynolds, C.I.E. (Member since 1872).

Biographical notices of members deceased will be found published in the *Journal*.

The complete list of those who have died during the past Session is as follows:—

Honorary Member.

E. Mascart.

Members.

Professor W. E. Ayrton, F.R.S.	F. A. C. Perrine.
E. J. Bristow.	R. Portelli.
W. P. J. Fawcus.	C. H. Reynolds, C.I.E.
Emil Naglo.	N. Rheam.

Douglas L. Wells.

Associate Members.

Alexander Adams.	C. G. Hampson.
Raymond Correa.	A. C. Hanson.
T. P. K. Hammarskjold.	H. T. Hincks.

W. W. Strode.

Associates.

Lord Blythswood, F.R.S.	R. Lewis.
L. L. Hartvigson.	J. Sheppard.
F. J. Lamb.	W. Teale.

A. R. Walker.

Students.

F. Collins.	K. Htu.
E. W. Heathcote.	E. Warnant.

RESIGNATIONS.

5 Members, 16 Associate Members, 31 Associates, and 57 Students have resigned since the date of the last Annual Report.

MEETINGS AND PAPERS.

During the past Session 16 General Meetings and 21 Council Meetings have been held. The usual standing Committees have met regularly throughout the Session, and several Occasional Committees appointed by the Council for the consideration of special matters coming before them have also met, the total number of Committee Meetings held during the Session being 95.

There have been 45 meetings of Local Sections, namely, at Birmingham 7, at Dublin 7, at Glasgow 7, at Leeds 6, at Manchester 11, and at Newcastle 7.

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Annual Dinners and other social functions were held at Birmingham, Dublin, Glasgow, Leeds, Manchester, and Newcastle, which were well attended by members and guests. Members of Council also availed themselves of the opportunities thus afforded of meeting the members resident in the Provinces.

The new method for dealing with papers offered to the Institution, introduced at the beginning of the Session 1907–8, continues to work satisfactorily, and several papers of importance have been read in London and at meetings of Local Sections, which, under the former system, would have been read at one place only.

It is hoped that members will avail themselves of the *Journal* to a greater extent than in the past as a medium for the publication of short Notes or Communications—not necessarily for reading or discussion at meetings—on new discoveries, methods of testing, and similar matters.

In November last Mr. W. Tatlow resigned the office of Honorary Secretary of the Dublin Local Section, an office which he had held since 1902. The Council desire to express their appreciation of Mr. Tatlow's services to the Institution, and particularly to the Dublin Local Section. The new Honorary Secretary is Mr. Thomas Tomlinson.

The following is the list of papers for the session, with the names of the authors and the places at which they were read :—

Title.	Author.	Where Read.
Inaugural Address of President.	W. M. Mordey, President.	London.
Chairman's Address.	G. F. Pilditch, Chairman.	Dublin.
Chairman's Address.	W. W. Lackie, Chairman.	Glasgow.
Chairman's Address.	H. E. Yerbury, Chairman.	Leeds.
Chairman's Address.	Miles Walker, Chairman.	Manchester.
Chairman's Address.	A. L. E. Drummond, Chairman.	Newcastle.
"The Use of Large Gas Engines for Generating Power."	L. Andrews, Member, and R. Porter, Associate Member.	London, Dublin, and Manchester.
"Some Considerations on the Manipulation of Dry-core Telephone Cables."	F. G. C. Baldwin, Associate Member.	Birmingham.
"Plans and Records for Electrical Distribution Systems."	J. W. Beauchamp, Associate Member.	Sheffield.
"Description of the Electro-hydraulic Pumping Plants at the Bristol Docks."	W. A. Clatworthy, Member.	Newcastle.
"The 'G.B.' System from a Tramway Manager's Point of View.	Stanley Clegg, Member.	London and Leeds

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TITLE.	AUTHOR.	WHERE READ.
"On a Method of using Transformers as Choking Coils, and its Application to the Testing of Alternators."	J. D. COALES, Associate Member.	Birmingham.
"Domestic Electricity Supply (including Heating and Cooking) as Affected by Tariffs."	W. R. COOPER, Member.	London, Dublin, and Glasgow.
"The Electric Discharge and Production of Nitric Acid."	W. CRAMP, Member, and B. HOYLE, Student.	London and Manchester.
"Electric Traction Vagabond Currents."	J. G. CUNLIFFE and R. G. CUNLIFFE, Students."	Manchester.
"Transformers; some Theoretical and Practical Considerations."	A. P. M. FLEMING and K. M. FAYE-HANSEN, Associate Members.	Manchester.
"Railway Signalling."	Capt. A. GARDINER, R.E., Associate.	Leeds.
"The Theory and Application of Motor Converters."	H. S. HALLO.	London.
"Interpole Designs."	W. B. HIRD, Member.	Glasgow.
"Practical Considerations in the Selection of Turbo-alternators."	Dr. M. KLOSS, Member.	Manchester and Birmingham.
"Early Experiments in Electric Traction."	W. W. LACKIE, Member.	Glasgow.
"Electric Street Lighting."	W. F. LONG, Associate Member.	Cape Town.
"Kapp-Hopkinson Test on a Single Direct-current Machine."	W. LULOFS.	Birmingham.
"Output and Economy Limits of Dynamo Electric Machinery."	J. C. MACFARLANE, Member, and H. BURGE, Associate Member.	London.
"Some Tests and Uses of Condensers."	W. M. MORDEY, President.	London.
"The Electrification of Steam-driven Non-reversing Rolling Mills."	W. F. MYLAN, Associate Member.	Leeds.
"Flywheel Load Equaliser."	J. S. PECK, Member.	Manchester.
"Economics of Medium-sized Power Stations. A Study of Comparisons between Steam, Gas, and Oil Engines."	A. J. J. PFEIFFER, Member.	London.

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TITLE.	AUTHOR.	WHERE READ.
"The Electrical System of the London County Council Tramways."	J. H. RIDER, Member.	London and Dublin.
"Commercial Electric Heating."	J. ROBERTS.	London.
"Electricity Works and Refuse Destructors."	J. A. ROBERTSON, Member.	Glasgow and Dublin.
"Parallel Working of Alternators."	Dr. E. ROSENBERG, Member.	London and Manchester.
"Working of Electrical Plants in Coal Mines."	S. A. SIMON, Associate Member.	Glasgow.
"The Testing of Alternators."	S. P. SMITH.	Birmingham.
"The Radiotelegraphic Station at Cullercoats."	A. SORENSEN.	Newcastle.
"Researches on the Magnetic Properties of a Series of Carbon Tungsten Steels."	T. SWINDEN.	Sheffield.
"Extending the Limits of Power Transmission.	A. M. TAYLOR, Member.	Birmingham.
"Improvement of Power Factor in Alternating-current Systems."	MILES WALKER, Member.	Manchester and Birmingham.
"The Di-electric Strength of Compressed Air."	E. A. WATSON, Student.	London.

In addition to the above-mentioned papers read at meetings the following have been accepted for printing in the *Journal*:—

ORIGINAL COMMUNICATIONS.

TITLE.	AUTHOR.
"Magnetic Reluctance of Joints in Transformer Iron."	Dr. H. BOHLE, Member.
"The German Standards and Regulations for Electrical Machinery."	N. C. BRIDGE.
"Experimental Analysis of Armature Reaction."	Dr. G. KAPP, Member.
"The Measurement of the Insulation Resistance of a Live Three-wire System."	Dr. G. KAPP, Member, and J. D. COALES, Associate Member.
"On the Measurement of Large Inductances containing Iron."	Sir OLIVER LODGE, F.R.S., Member, and B. DAVIES, Associate Member.
"Investigations on the Electrical State of the Upper Atmosphere."	W. E. MAKOWER, E. MARSDEN, and MARGARET WHITE.
"Non-inductive, Water-cooled Standard Resistances for Precision Alternating-current Measurements."	C. C. PATERSON and E. H. RAYNER, Associate Members.

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Scholarships.

The Council have awarded a Salomons Scholarship, value £50, to Mr. John Mould, of the Finsbury Technical College, London; and a David Hughes Scholarship, value £50, to Mr. Herbert Maxwell Browne, of King's College, London.

Satisfactory reports on the work of last year's scholars, Messrs. H. Carnegie, C. Higgins, and A. Hutt, have been received from the Professors under whom they are working, Mr. Carnegie at the Karlsruhe Technical High School, and Messrs. Higgins and Hutt at the Central Technical College.

Annual Premiums.

The following premiums for papers and communications have been awarded by the Council this year. In accordance with precedent, in deciding upon these awards the Council have not taken into account papers contributed by members at present holding office on the Council.

The Institution Premium, value £25,

to Mr. J. H. Rider (Member), for his paper on "The Electrical System of the London County Council Tramways."

The Paris Electrical Exhibition Premium, value £10,

to Messrs. L. Andrews (Member) and R. Porter (Associate Member), for their paper on "The Use of Large Gas Engines for Generating Power."

An Extra Premium, value £10,

to Messrs. W. Cramp (Member) and B. Hoyle (Student), for their paper on "The Electric Discharge and Production of Nitric Acid."

An Extra Premium, value £10,

to Mr. T. Swinden, for his paper "Researches on the Magnetic Properties of a Series of Carbon Tungsten Steels."

An Extra Premium, value £10,

to Mr. E. A. Watson (Student), for his paper on "The Di-electric Strength of Compressed Air."

An Extra Premium, value £5,

to Mr. H. S. Hallo, for his paper on "The Theory and Application of Motor Converters."

An Extra Premium, value £5,

to Messrs. J. C. Macfarlane (Member) and H. Burge (Associate Member), for their paper on "Output and Economy Limits of Dynamo Electric Machinery."

An Extra Premium, value £5,

to Mr. J. S. Peck (Member) for his paper "Fly Wheel Load Equalisers."

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AN ORIGINAL COMMUNICATION PREMIUM, value £10,

to Messrs. C. C. PATERSON and E. H. RAYNER (Associate Members), for their communication "Non-inductive, Water-cooled Standard Resistances for precision Alternating Current Measurements."

STUDENTS' PREMIUMS.

A First Student's Premium, value £10, to Messrs. B. E. STOTT and J. HARGROVE (Manchester), for their paper "The Design of Small Direct Current Machines."

A Second Student's Premium, value £5, to Mr. L. H. A. CARR (Manchester), for his paper "Notes on the Elimination of Sparking."

Three Extra Students' Premiums, each of the value of £5, to Mr. P. C. JONES (Manchester), for his paper on "The Single-phase Railway"; to Mr. W. S. LONSDALE (Singapore), for his paper on "The Direct Current Variable Speed Motor and its Application to Modern Machine Tools"; to Mr. C. S. RICHARDS (Manchester), for his paper on "The Utilisation of Exhaust Steam for Electric Driving."

WILLANS PREMIUM.

In conjunction with the Institution of Mechanical Engineers, a gold medal has been designed for presentation to those recipients of the Willans Premium who may prefer to receive the award in this form. One side of this medal bears a portrait head of the late Mr. Peter William Willans; on the other side is an allegorical figure, the names of the two Institutions being inscribed, together with the name of the recipient and the year of the award. Bronze replicas have been presented to Mr. Mark Robinson and to Mr. P. V. McMahon, to whom the Council awarded the Willans Premium in 1897 and in 1904 respectively.

STUDENTS' SECTION.

At the opening meeting of their session an address to the students was delivered by Mr. J. S. Highfield on the subject of "The Responsibility of the Engineer."

Ten meetings altogether of the Students' Section have been held in the Library of the Institution, at which nine papers have been read and discussed. The Students' Committee organised a visit to Newcastle-on-Tyne in the summer of 1908, where they visited the following works and places of interest: Messrs. Armstrong, Whitworth & Co., Elswick; Messrs. Hawthorn, Leslie & Co.; Messrs. J. H. Holmes & Co.; the Newcastle-on-Tyne Electric Supply Company; the Consett Iron Works; Messrs. Swan, Hunter, and Wigham Richardson (shipyard); Messrs. Ernest Scott and Mountain, Ltd.; Messrs. Clark, Chapman & Co.; Midland Railway, Derby; and the Hordern Collieries. The party was everywhere most kindly and hospitably received.

The Annual Dinner of the Students' Section, held on February 24th, was well attended.

The Glasgow and Manchester Branches of the Students' Section

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have also completed a successful session, having held eight meetings and nine meetings respectively. Visits to various works were also organised by kind permission of the firms concerned.

The Students' Committees and their Honorary Secretaries are to be congratulated on the success of Students' Meetings and Visits.

The list of students' papers for which premiums have been awarded is given above.

Secretaryship.

In November last Mr. G. C. Lloyd resigned the Secretaryship, to take up the position of Secretary to the Iron and Steel Institute, in whose service he had been engaged for several years before being appointed by this Institution. The Council, in accepting the resignation, placed on record their appreciation of the valuable services rendered by Mr. Lloyd during his five years' tenure of office.

In response to advertisements, many applications for the position were received. These were carefully considered, and several candidates, whose qualifications appeared to meet the requirements, were interviewed. The Council appointed Mr. P. F. Rowell, who had been a member of the Secretary's staff since 1901, and had held for the last five years the position of Assistant Secretary.

The Institution Building.

On June 30, 1908, a Special General Meeting * of Members, Associate Members, and Associates authorised the purchase, for a sum of £50,000, of the lease of the site and the building on the Victoria Embankment belonging to, and in the possession of, the Royal College of Physicians and the Royal College of Surgeons.

It is sufficient to state here that the building occupies a site more than 20,000 square feet in area and is held on a lease, with seventy-five years unexpired from June 1909, at an annual ground rent of £2,201. The Council have entered into an agreement to complete the purchase by June 1, 1909.

For the present, the Institution will occupy the whole of the ground floor and a large portion of the first floor, which will form a Library, of nearly 3,000 square feet, facing the river. It is proposed to enlarge and improve the Entrance Hall and the Lecture Theatre. The remaining portion of the building has been let for three years to the present owners, the Royal Colleges of Physicians and Surgeons. It is expected that the Institution will be transferred to the new building in the autumn, and that the enlarged Theatre will be available early in 1910.

"Science Abstracts."

This publication is progressing satisfactorily. The volumes for 1908 were of nearly the same size as those for 1907, and the arrangements for ensuring the prompt publication of abstracts of scientific and technical articles have worked well.

* *Journal*, vol. 41, p. 851 (1908).

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The British Electrotechnical Committee.

The British Committee for 1909 is constituted as follows :—

Colonel R. E. Crompton, C.B.
Mr. W. Duddell, F.R.S.
Mr. Kenelm Edgcumbe.
Sir John Gavey, C.B.
Dr. R. T. Glazebrook, F.R.S.
Mr. Robert Kaye Gray.
Mr. Robert Hammond.
Colonel H. C. L. Holden, F.R.S.
Dr. Gisbert Kapp.
Mr. T. Mather, F.R.S.
Mr. H. W. Miller.
Mr. W. M. Mordey.
Sir William H. Preece, K.C.B., F.R.S.
The Rt. Hon. Lord Rayleigh, O.M., F.R.S.
Captain H. R. Sankey, R.E. (ret.).
Mr. Alexander Siemens.
Mr. C. P. Sparks.
Mr. J. Swinburne, F.R.S.
Dr. S. P. Thompson, F.R.S.
Mr. A. P. Trotter.
Mr. E. B. Vignoles.
Mr. C. H. Wordingham.

Mr. C. le Maistre (*Secretary*).

Since the last report the British Electrotechnical Committee and the Sub-Committees on Nomenclature, Symbols, and the International Unit of Light have held eight meetings. The list of terms with explanations under preparation by the Sub-Committee on Nomenclature has now been completed as far as the letter E, and it will shortly be circulated to the various Committees abroad. The Sub-Committee on Symbols have only held one meeting, on account of the absence of the Chairman, Lord Rayleigh.

The British Committee have forwarded to the Central Offices a proposal with regard to an International Unit of Light, and the matter is now before the several Electrotechnical Committees.

At the Council meeting of the International Electrotechnical Commission, in October, 1908, the British delegates were Sir John Gavey, C.B., and Dr. S. P. Thompson, F.R.S. An address of welcome was given by the Right Hon. A. J. Balfour, M.P., and subsequently Professor Elihu Thomson was elected President in succession to the late Lord Kelvin, and Colonel R. E. Crompton, C.B., was re-elected Hon. Secretary.

Wiring Rules.

A new edition of the Wiring Rules is in course of preparation. This will contain certain modifications to meet the new Regulations of the Home Office, and provision will be made to sanction certain less expensive methods of wiring and to extend the Rules for work at very low pressures. It is hoped to issue this revised edition before the end of the year.

Professional Conduct.

The Council have under consideration the issue of a statement on the subject of professional conduct, a matter which has recently engaged the attention of the Institution of Civil Engineers,

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Examinations for Associate Membership.

The Council are considering the question of requiring candidates for Associate Membership to pass a qualifying examination.

Building Fund.

The attention of members generally is called to this Fund. The Council express the hope that there will be a large increase in the number of contributors, and they wish to point out the importance, in the aggregate, of even small annual subscriptions.

Benevolent Fund.

The Committee of Management report that the Benevolent Fund of the Institution shows a satisfactory increase for the past year. On December 31, 1908, the capital account of the Fund stood at £3,000, as compared with £2,735 9s. 11d. at the end of 1907. The donations to the Fund in 1908 include one of £105 from Mr. W. B. Esson and another of £75 from the Committee of the Electrical Engineers' Ball. The Council desire to acknowledge their indebtedness to the generosity of these and other donors and subscribers who have supported the Fund.

The Wilde Benevolent Trust Fund stands at £1,744 16s. Grants in aid have been made from the income of both Funds during 1908.

Annual Accounts.

The Report of Mr. Robert Hammond, the Hon. Treasurer, shows that the balance carried to the General Fund at the end of 1908, being excess of income over expenditure, was £3,253 9s. 3d., as compared with £3,678 9s. 2d. for 1907, showing a decrease of £424 19s. 11.

The transfers to the Building Fund during the year 1908 included a transfer of dividends amounting to £446 8s.

Balance Sheet.—The balance sheet sets out the total investments other than the investments of the Trust Funds. It will be seen that the total assets amount to £51,552 11s. 1d., against which are to be set liabilities amounting to £1,064 19s. 5d., leaving as the net assets of the Institution £50,487 11s. 8d.

The investments in stocks and shares included in the above appear in the accounts at cost price with a book value of—

	£	s.	d.
Life Compositions	5,555	12	0
Entrance Fees...	1,209	7	0
Building Fund	16,322	13	2
General Fund	3,338	14	5
Kelvin Lecture Fund...	862	10	10
	£27,288	17	5

and their value at the current market prices on April 29th was £24,720.

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Trust Funds.—No alteration has taken place in these three Funds during the year under consideration.

Life Compositions.—This Fund still stands, as reported last year, at £5,581 13s.

Entrance Fees Fund.—The Fund has increased during the year by £701 17s., but the total has been decreased by £3,719 12s. 11d., transferred to the Building Fund. The total now stands at £1,437 6s. 7d.

Building Fund.—It will be noticed that the Fund has increased during 1908 by the amount of £1,219 11s. 2d., the increase being due to revenue from property, subscriptions, dividends on investments, and sundry other items.

Out of the available balance of £1,335 3s. 3d., there has been invested during the year on account of this Fund—

	£	s.	d.
£700 Birmingham Corporation 3 per cent. Stock	614	6	0
£700 Bradford Corporation 3 per cent. Stock	609	1	0
	£1,223	7	0

General Fund.—This Fund has increased to the extent of £3,253 9s. 3d., and after deducting the transfer to Building Fund, now stands at £6,852 6s. 9d. The investments on account of this Fund during the year were as follows:—

	£	s.	d.
£600 Belfast Corporation 3½ per cent. Stock	592	13	6
£500 Bristol „ 3½ „ „	501	6	0
£500 Leicester „ 3½ „ „	503	16	0
	£1,597	15	6

Summary.—The increases of the Funds during the year are as follows:—

	£	s.	d.
Entrance Fees...	701	17	0
Building Fund	1,219	11	2
General Fund	3,253	9	3
	£5,174	17	5

Museum.

Several interesting pieces of apparatus have been added during the year. The Institution is under a deep obligation to the Postmaster-General, who has kindly arranged that, in future, duplicates of speci-

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mens of telegraphic and telephonic apparatus selected for the Post Office Museum shall be sent to the Institution Museum. The attention of members is called to the desirability of reporting to the Institution the existence of any objects of historical interest connected with Electrical Science and Industry which may appear suitable for inclusion in the Museum.

LIBRARY.

Early in 1908 the Council, under the advice of the Honorary Solicitors, considered the steps that should be taken for the appointment of new Trustees for the Ronalds Library. The original Trustees, appointed in 1875, were Mr. S. Carter, Dr. E. Ronalds, Mr. J. C. Carter, Mr. J. M. Fletcher, Sir William Thomson (Lord Kelvin), Mr. Latimer Clark, Mr. Charles William Siemens, F.R.S., D.C.L. (Sir William Siemens), and Major Frank Bolton (Sir Francis Bolton). At a meeting of the surviving Trustees, Mr. J. C. Carter and Mr. J. M. Fletcher, who continue to act, the following new Trustees were appointed : Colonel R. E. Crompton, C.B. (President), Dr. R. T. Glazebrook, F.R.S. (Past-President), Sir John Gavey, C.B. (Past-President), Mr. W. Duddell, F.R.S. (Chairman of Library Committee), Mr. B. Ronalds and Mr. R. Carter (both great-nephews of the late Sir Francis Ronalds).

The Council have now acquired 1,442 out of the 1,623 works which were reported to be wanting to complete the Institution's collection of electrotechnical literature. In addition to these, the number of new books purchased since May 20, 1908, is 125, and 362 books and pamphlets have been presented by members, publishers, and kindred societies. The number of members who consult the Library continues to increase, the total number of readers during the past twelve months having been 903, of whom 41 were non-members.

APPENDIX TO REPORT.

TRANSACTIONS, PROCEEDINGS, ETC., RECEIVED BY THE INSTITUTION.

BRITISH.

British Association for the Advancement of Science, Reports.
Cambridge Philosophical Society, Proceedings.
Chartered Institute of Patent Agents, Transactions.
Civil and Mechanical Engineers' Society, Transactions.
Faraday Society, Transactions.
Greenwich Magnetical and Meteorological Observations.

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Illuminating Engineering Society, Transactions.
Incorporated Municipal Electrical Association, Proceedings.
Institute of Chemistry, Proceedings.
Institute of Marine Engineers, Transactions.
Institute of Metals, Journal.
Institution of Civil Engineers, Proceedings.
Institution of Engineers and Shipbuilders in Scotland, Transactions.
Institution of Mechanical Engineers, Proceedings.
Institution of Mining and Metallurgy, Transactions and Bulletins.
Institution of Naval Architects, Transactions.
Institution of Post Office Electrical Engineers, Papers.
Iron and Steel Institute, Journal.
Liverpool Corporation Tramways, Annual Reports.
Liverpool Engineering Society, Proceedings.
Manchester Literary and Philosophical Society, Memoirs and Proceedings.
National Physical Laboratory Reports.
North-East Coast Institution of Engineers and Shipbuilders, Transactions.
North of England Institute of Mining and Mechanical Engineers' Transactions.
Physical Society, Proceedings.
Röntgen Society, Journal.
Royal Dublin Society, Transactions and Proceedings.
Royal Engineers' Institute, Proceedings.
Royal Institution, Proceedings.
Royal Meteorological Society, Quarterly Journal.
Royal Scottish Society of Arts, Transactions and Journal.
Royal Society, Philosophical Transactions and Proceedings.
Royal Society of Arts, Journal.
Royal Society of Edinburgh, Transactions and Proceedings.
Royal United Service Institution, Journal.
Society of Chemical Industry, Journal.
Society of Engineers, Proceedings.
Surveyors' Institution, Transactions and Professional Notes.
Tramways and Light Railways' Association, Official Circular.

COLONIAL.

Canadian Society of Civil Engineers, Transactions.
Engineering Association of New South Wales, Proceedings.
Engineering Society of Toronto, Transactions.
Indian Telegraph Department, Administration Reports.
Nova Scotia Institute of Science, Transactions and Proceedings.
Royal Society of Queensland, Proceedings.
Royal Society of Victoria, Proceedings.
South Australia, Meteorological Observation Reports.
Sydney University of Engineering, Proceedings.

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AMERICAN.

American Academy of Arts and Sciences, Proceedings.
American Institute of Electrical Engineers, Transactions and Proceedings.
American Electrochemical Society, Transactions.
American Institute of Mining Engineers, Transactions and Bi-Monthly Bulletin.
American Philosophical Society, Proceedings.
American Society of Civil Engineers, Proceedings.
American Society of Mechanical Engineers, Transactions and Proceedings.
Bureau of Standards, Washington, Bulletin.
Engineers' Club of Philadelphia, Proceedings.
Franklin Institute, Journal.
Ordnance Department of the United States, Notes.
Philadelphia Electrical Bureau, Annual Reports.
Smithsonian Institution, Reports, Miscellaneous Collections and Contributions to Knowledge.
U.S. Official Patent Gazette.
Western Society of Engineers, Journal.

AUSTRIAN.

Kaiserliche Akademie der Wissenschaften, Wien, Sitzungsberichte.

BELGIAN.

Association des Ingénieurs Électriciens sortis de l'Institut Electrotechnique Montefiore, Bulletin.
Société Belge d'Électriciens, Bulletin.

DUTCH.

Koninklijk Institut van Ingenieurs, Tijdschrift.
Koninklijke Akademie van Wetenschappen, Amsterdam, Proceedings.

FRENCH.

Académie des Sciences, Comptes Rendus Hebdomadaires des Séances.
Bureau des Longitudes, Annuaire.

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Société des Anciens Élèves des Écoles Nationales d'Arts et Metiers Bulletin Technologique.
Société des Ingénieurs Civils, Mémoires.
Société Française de Physique, Bulletin des Séances.
Société Internationale des Électriciens, Bulletin.
Société Scientifique Industrielle de Marseille, Bulletin.

GERMAN.

Physikalische Technische Reichsanstalt, Abhandlungen.
Schiffbautechnische Gesellschaft, Jahrbuch.
Verein Deutscher Ingenieure, Zeitschrift.
Verein zur Beförderung des Gewerbfleisses, Verhandlungen.

ITALIAN.

Associazione Elettrotecnica Italiana, Atti.
Reale Accademia dei Lincei, Atti e Memorie.

SWEDISH.

K. Svenska Vetenskaps-Akademien, Arkiv för Matematik, etc.

SWISS.

Association Suisse des Electriciens, Annuaire.

LIST OF PERIODICALS RECEIVED BY THE INSTITUTION.

BRITISH.

Automobile Owner.
Cassier's Magazine.
Central.
Colliery Guardian.
Electrical Bulletin.
Electrical Engineer.
Electrical Engineering.
Electrical Industries.
Electrical Magazine.
Electrical Review.
Electrical Times.
Electrician.
Electricity.

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Electron.
Engineer.
Engineering.
Engineering Magazine.
Engineering Review.
English Mechanic.
Illuminating Engineer.
Illustrated Official Journal, Patents.
Indian and Eastern Engineer.
International Marine Engineering.
Iron and Coal Trades Review.
Light Railway and Tramway Journal.
Mechanical Engineer.
Mining Journal.
National Telephone Journal.
Nature.
Page's Weekly.
Philosophical Magazine.
Post Office Electrical Engineers' Journal.
Railway News.
Railway Times.
Royal Engineers' Journal.
Scientific Monthly.
Tramway and Railway World.
Vulcan.

AMERICAN.

American Journal of Science.
American Telephone Journal.
Electric Journal.
Electric Railway Journal.
Electrical Review and Western Electrician.
Electrical World.
Electrochemical and Metallurgical Industry.
Engineering News.
India Rubber World.
Journal of the Telegraph.
Physical Review.
Scientific American.
Telephony.
Terrestrial Magnetism and Atmospherical Electricity.

AUSTRIAN.

Elektrotechnik und Maschinenbau.

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DANISH.

Teknisk Tidsskrift.

DUTCH.

De Ingenieur.

FRENCH.

Archives des Sciences Physiques et Naturelles.
Électricien.
Houille Blanche.
Industrie Électrique.
Journal de Physique.
Journal Télégraphique.
Lumière Électrique.
Mois Scientifique et Industriel.
Portefeuille Économique des Machines.
Revue Électrique.

GERMAN.

Annalen der Elektrotechnik.
Annalen der Physik.
Annalen der Physik, Beiblätter.
Elektrische Kraftbetriebe und Bahnen.
Elektro-Ingenieur Kalender (Hirsch und Wilking).
Elektrotechnische und Polytechnische Rundschau.
Elektrotechnische Zeitschrift.
Elektrotechnischer Anzeiger.
Fortschritte der Elektrotechnik.
Glückauf.
Jahrbuch der Elektrochemie.
Physikalische Zeitschrift.
Technische Literatur.
Zeitschrift für Elektrochemie.
Zeitschrift für Instrumentenkunde.

ITALIAN.

L'Elettricista.
L'Elettricita.
Giornale del Genio Civile.
Il Nuovo Cimento.

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SIAMESE.

Siam Engineering.

SPANISH.

La Ingenieria.
Revista Electro-Industrial.

SWISS.

Schweizerische Elektrotechnische Zeitschrift.

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The Institution of

STATEMENT OF INCOME AND

ENDED 31st

Dr.

EXPENDITURE.

	£ s. d.	£ s. d.
To Management :—		
Salaries	1,918 5 10	
Retiring Allowance	125 0 0	
Accountants' Fees	21 0 0	
Printing, Stationery, and Addressing ...	591 18 3	
Postage	912 0 2	
Telephone	27 2 0	
Travelling	202 13 1	
		3,797 19 4
„ Rent, Insurance, Lighting, and Firing ...	... ...	717 7 10
„ Office Redecoration and Fittings	... ...	23 15 6
„ Publications :—		
Journal	1,490 1 5	
"Science Abstracts"—		
Disbursements £1,799 16 10		
Less Receipts 1,377 9 0		
	422 7 10	
		1,912 9 3
„ Meetings :—		
Advance Proofs, Refreshments, &c.	193 8 5	
Reporting	76 7 0	
		269 15 5
„ Local Sections	... ...	565 18 8
„ Premiums	... ...	133 18 2
„ British Electrotechnical Committee ...	... ...	257 4 0
„ Conversazione	... ...	242 1 10
„ Annual Dinner	... ...	122 0 3
„ Museum	... ...	28 18 6
„ Depreciation :—		
Library (10 %)	173 1 7	
Furniture (5 %)	21 15 0	
		194 16 7
„ Miscellaneous Expenses	... ...	103 12 8
„ Balance carried to General Fund, being excess of Income over Expenditure	... ...	3,253 9 3
		£11,623 7 3

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Electrical Engineers.

EXPENDITURE FOR THE YEAR DECEMBER, 1908.

Cr.

INCOME.

	£	s.	d.	£	s.	d.
By Subscriptions	...		...	10,590	9	0
„ Dividends on Investments :—						
Life Compositions Fund	£173	9	5			
General and Entrance Fees Funds	158	2	8			
				331	12	1
„ Interest on Cash on Deposit	...		...	18	3	10
„ Journal :—						
Sales	193	16	1			
Advertisements	465	2	6			
				658	18	7
„ Wiring Rules	...		...	16	13	9
„ Model General Conditions for Contracts	...		...	7	10	0
				£11,623	7	3

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BALANCE SHEET,

Dr.

LIABILITIES.

			£ s. d.
To Salomons Scholarship Trust Fund (Income)			23 19 2
„ David Hughes Scholarship Trust Fund :—			
Capital uninvested	1 5 0		
Income	25 0 7		
			26 5 7
„ Wilde Benevolent Trust Fund (Income)...			134 15 4
„ Life Compositions Fund			5,581 13 0
„ Entrance Fees Fund			1,437 6 7
„ Building Fund			35,753 14 6
„ Kelvin Lecture Fund			862 10 10
„ Sundry Creditors			740 5 9
„ Local Sections :—			
Due to Hon. Sec. Birmingham Section ...	5 19 0		
„ „ Dublin ...	1 12 0		
„ „ Newcastle „ ...	4 0 7		
			11 11 7
„ Subscriptions received in advance			88 12 0
„ Foreign Visit Fund			39 10 0
„ General Fund			6,852 6 9

ROBERT HAMMOND,
Honorary Treasurer.

P. F. ROWELL,
Secretary.

£51,552 11 1

We beg to report that we have audited the Balance Sheet of the Institu- together with the annexed Statements of Account. We have obtained all the Bankers' Certificates of Investments and the Title Deeds of the Tothill Sheet is properly drawn up so as to exhibit a true and correct view of the and the explanations given to us and as shown by the books of the

ALLEN, BIGGS & CO.,
Chartered Accountants.
147, Leadenhall Street, E.C.

April 27, 1909.

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31st DECEMBER, 1908.

Cr.

ASSETS.

			£	s.	d.
By Life Compositions Fund Investments (at cost)	...	...	5,555	12	0
„ Building Fund Investments	„	...	16,322	13	2
„ Tothill Street Buildings and Site	„	...	19,260	17	1
„ Institution Building :—					
Surveyors' Fees, &c.	...	...	58	8	0
„ Entrance Fees Fund Investments	„	...	1,209	7	0
„ General Fund Investments	„	...	3,338	14	5
„ Kelvin Lecture Fund Investment	„	...	862	10	10
„ Sundry Debtors	..	...	1,215	13	0
„ Local Sections :—					
Cash in hands of Hon. Sec. Glasgow Section	16 10 5				
do. do. do. Leeds do.	36 7 6				
do. do. do. Manchester do.	4 5 11				
			57	3	10
„ Furniture	...	...	413	6	10
„ Library	...	...	1,557	14	11
„ Vellum Diploma Forms			2	13	1
„ Cash :—At Bankers'	1,483 17 1				
Petty Cash	79 4 6				
P. O. Savings Bank (Wilde Benevolent Trust Fund Income)	134 15 4				
			1,697	16	11
			£51,552	11	1

tion of Electrical Engineers, dated 31st December, 1908, and above set forth, information and explanations we have required. We have inspected the Street Property. In our opinion the Statements are correct, and the Balance state of the Institution s affairs according to the best of our information Institution.

R. S. ERSKINE,
SIDNEY SHARP, } *Honorary Auditors.*

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SALOMONS SCHOLARSHIP

Dr.

	£	s.	d.
To Amount (as per last Account)	2,126	19	3
	£2,126	19	3

SALOMONS SCHOLARSHIP

Dr.

	£	s.	d.
To Amount paid to Scholars in 1908...	75	0	0
„ Balance carried to Balance Sheet	23	19	2
	£98	19	2

DAVID HUGHES SCHOLARSHIP

Dr.

	£	s.	d.
To Amount (as per last Account)	2,000	0	0
	£2,000	0	0

DAVID HUGHES SCHOLARSHIP

Dr.

	£	s.	d.
To Amount paid to Scholars in 1908...	50	0	0
„ Balance carried to Balance Sheet	25	0	7
	£75	0	7

WILDE BENEVOLENT

Dr.

	£	s.	d.
To Amount (as per last Account)	1,744	16	0
	£1,744	16	0

WILDE BENEVOLENT

Dr.

	£	s.	d.
To Grant made in 1908	8	0	0
„ Balance carried to Balance Sheet	134	15	4
	£142	15	4

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TRUST. FUND.

	Cr. £ s. d.
By Investments (at cost) :—	
£1,500 New South Wales 3½ % Stock	1,556 5 9
£500 Cape of Good Hope 3½ % Stock	570 13 6
	£2,126 19 3

TRUST FUND (Income).

	Cr. £ s. d.
By Balance (as per last Account)	28 19 2
„ Dividends received in 1908	70 0 0
	£98 19 2

TRUST FUND.

	Cr. £ s. d.
By Investment (at cost) :—£2,045 Staines Reservoirs 3 % Guaranteed Debenture Stock	1,998 15 0
„ Balance carried to Balance Sheet	1 5 0
	£2,000 0 0

TRUST FUND (Income).

	Cr. £ s. d.
By Balance (as per last Account)	13 13 7
„ Dividends received in 1908	61 7 0
	£75 0 7

TRUST FUND.

	Cr. £ s. d.
By Investments (at cost):—	
£875 Great Eastern Railway Metropolitan 5 % Guaranteed Stock	1,493 16 3
£215 North Eastern Railway 4 % Guaranteed Stock ...	250 19 9
	£1,744 16 0

TRUST FUND (Income).

	Cr. £ s. d.
By Balance (as per last Account)	87 18 6
„ Dividends received in 1908	52 7 0
„ Interest do. do.	2 9 10
	£142 15 4

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LIFE COMPOSITIONS

Dr.

	£	s.	d.
To Amount (as per last Account)	5,581	13	0
	£5,581	13	0

ENTRANCE FEES

Dr.

	£	s.	d.
To Entrance Fees from 1902 to 1907 (as per last Account) ...	4,455	2	6
„ „ „ received in 1908	701	17	0
	5,156	19	6
Less Transferred to Building Fund	3,719	12	11
	£1,437	6	7

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FUND.

Cr.

	£	s.	d.
By Investments (at cost) :—			
£318 0 0 Cape of Good Hope 4 % Consolidated Stock	306	0	0
1,679 19 5 India 3½ % Stock	1,776	5	0
120 0 0 South-Eastern Railway 5 % Debenture Stock	204	16	6
355 5 10 Canada 3 % Stock	352	13	6
289 17 4 Midland Railway 2½ % Consolidated Perpetual Preference Stock	274	11	10
6 0 0 East Indian Railway Class "C" Annuity ...	185	1	9
87 0 0 Great Eastern Railway 4 % Consolidated Preference Stock	130	15	2
175 0 0 Great Eastern Railway 4 % Debenture Stock	251	5	5
5 6 4 Great Indian Peninsula Railway "B" Annuity	133	17	6
190 13 4 Metropolitan Water Board "A" Stock ...	207	17	9
520 0 0 Staines Reservoirs 3 % Guaranteed Debenture Stock	539	2	3
200 0 0 Glasgow and South-Western Railway 4 % Preference Stock (1894)	276	5	0
1 11 8 Madras Railway "B" Annuity	44	9	4
60 0 0 South Indian Railway 4½ % Debenture Stock	88	1	4
30 0 0 Burma Railway Co.'s Stock	30	12	3
40 0 0 East Indian Railway 4½ % Debenture Stock ...	57	3	7
400 0 0 Natal Zululand Railways 3 % Debentures ...	351	1	0
350 0 0 New Zealand 3½ % Inscribed Stock	345	12	10
	£5,555	12	0
„ Balance Uninvested	26	1	0
	£5,581	13	0

FUND.

Cr.

	£	s.	d.	£	s.	d.
By Investments (at cost) during 1908 :—						
£800 Leeds Corporation 2½% Stock	588	1	0			
£700 Liverpool Corporation 3% Stock... ...	621	6	0			
				1,209	7	0
„ Balance Uninvested				227	19	7
				£1,437	6	7

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BUILDING

Dr.

	£	s.	d.
To Amount (as per last Account)	21,375	12	5
„ „ transferred from Entrance Fees Fund	3,719	12	11
„ „ „ „ General Fund	9,438	18	0
„ Dividends on Investments	478	16	10
„ Revenue from Property	659	4	0
„ Subscriptions	75	9	0
„ Surplus from Vellum Diplomas	6	1	4
	£35,753	14	6

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FUND.

Cr.

	£	s.	d.	£	s.	d.
By Investments (at cost) :—						
As per last Account (prior to 1908)						
£1,000 South-Eastern Railway 5 % Debenture Stock	1,447	1	9			
£550 Manchester Corporation 3 % Stock ...	493	13	6			
				1,940	15	3
Purchased during 1908 :—						
£700 Birmingham Corporation 3% Stock...	614	6	0			
£700 Bradford „ 3% „ ...	609	1	0			
				1,223	7	0
Transferred from Entrance Fees Fund in 1908 :—						
£1,418 8 0 Midland Railway 2½% Consolidated Perpetual Preference Stock...	1,200	0	0			
918 3 2 India 3½ % Stock	973	17	10			
410 0 0 East Indian Railway 4½ % Debenture Stock	586	1	7			
800 0 0 North Eastern Railway 4 % Preference Stock	959	13	6			
				3,719	12	11
Transferred from General Fund in 1908 :—						
£52 13 8 Great Indian Peninsula Railway "B" Annuity	1,239	17	9			
39 7 7 Madras Railway "B" Annuity ...	1,114	14	0			
623 0 0 Great Western Railway 5 % Preference Stock	999	18	1			
2,200 0 0 Natal Zululand Railways 3 % Debentures	1,919	11	0			
650 0 0 New Zealand 3½ % Inscribed Stock	641	18	2			
1,100 0 0 Great Eastern Railway 4 % Consolidated Preference Stock ...	1,266	18	9			
1,050 0 0 London and North Western Railway 4 % Preference Stock ...	1,225	4	9			
700 0 0 Great Eastern Railway Metropolitan 5 % Guaranteed Stock ...	1,030	15	6			
				9,438	18	0
				16,322	13	2
„ Tothill Street Buildings and Site (as per last Account) ...				19,260	17	1
„ Institution Building :—						
Surveyors' Fees, &c.				58	8	0
„ Balance Uninvested				111	16	3
				£35,753	14	6

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GENERAL

Dr.

	£	s.	d.
To Excesses of Income over Expenditure, to Dec. 31, 1907 * ...	30,098	19	8
Add Excess of Income over Expenditure for 1908	3,253	9	3
	33,352	8	11
Less Transfers to Building Fund :—			
Previous to 1908 ... . 16,198 13 4			
During 1908 ... ... 9,438 18 0			
25,637 11 4			
Transfer to Kelvin Lecture Fund 862 10 10			
	26,500	2	2

* Made up as follows :—

Amount as per last Balance Sheet ...	13,900	6	4
Add Transfers to Building Fund previous to 1908	16,198	13	4
	£30,098	19	8

£6,852 6 9

KELVIN

Dr.

	£	s.	d.
To Transfer from General Fund	862	10	10
„ Dividends 25 0 0			
Less Lecturer's Honorarium 25 0 0			
	£862	10	10

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FUND.

Cr.

			£ s. d.
By Investments (at cost) :—			
£1,500 Great Central and Midland Railway 3½ % Guaranteed Stock	1,568 8 9		
£200 2½ % Consols	172 10 2		
		1,740 18 11	
„ Investments during 1908 :—			
£600 Belfast Corporation 3½ % Stock	592 13 6		
£500 Bristol „ 3½ % „	501 6 0		
£500 Leicester „ 3½ % „	503 16 0		
		1,597 15 6	
		3,338 14 5	
„ Balance made up as follows :—			
ASSETS.			
Sundry Debtors	1,215 13 0		
Cash in Hand	1,755 0 9		
Furniture	413 6 10		
Library	1,557 14 11		
Vellum Diploma Forms ...	2 13 1		
	4,944 8 7		
LIABILITIES.			
Uninvested Balances of Special Funds	590 6 11		
Sundry Creditors	751 17 4		
Subscriptions in Advance	88 12 0		
	1,430 16 3		
		3,513 12 4	
		£6,852 6 9	

LECTURE FUND.

Cr.

	£ s. d.
By Investment (at cost) :—	
£1,000 2½ % Consols	862 10 10
	£862 10 10

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LIBRARY.

Dr.

	£	s.	d.
To Amount (as per Balance Sheet)	1,557	14	11
	£1,557	14	11

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LIBRARY.

Cr.

	£	s.	d.
Outlays on Books, Pictures, etc., up to December 31, 1907 ...	2,145	12	3
Less Provision for Depreciation (1901–7)	646	5	8
As per last Balance Sheet	1,499	6	7
Expenditure on Books and Binding in 1908	231	9	11
	1,730	16	6
Less 10% Depreciation for 1908	173	1	7
	£1,557	14	11

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The PRESIDENT: It is now my duty to present the Annual Report. With your permission I will do so only in abstract, and as the Honorary Treasurer is here I will omit any references to the financial parts of the Report, and will ask him to deal with those questions. [The President then read the Annual Report, and in the course of doing so made the following comments:] With reference to the use of the *Journal* for the publication of short notes or communications, the Council hopes that when members have short announcements to make, such as notes on processes, methods of testing, new instruments, and so on, they will send them to the *Journal*. We think it desirable that short notes of that nature should find a place in the *Journal*, so that they may reach the greatest number of members. It is the best way of getting a permanent record of such matters. Whilst we all realise the great services that are done to the industry by the technical papers, I am sure none of our friends of the technical press will misunderstand me when I say that the *Journal* of this Institution is a very suitable place for the publication of such notes by our members. The technical papers necessarily have to deal with a large mass of matter, much of which is of merely temporary interest. Notes such as I have in mind, usually of permanent scientific interest, are apt to get buried in the heavy volumes of the technical papers. We hope that notes that may appear in the *Journal* will also appear in the technical papers, and that the authors of such notes will not lose the publicity that they naturally and properly value. I trust that the short list of Original Communications in the Report will become longer as years go on.

Coming to the question of the Annual Premiums, the Fahie Premium has not been awarded this year. As you know, it is the custom of the Council to award that premium for papers on telegraphic subjects, but we very much regret that no paper has been received this year for which the author could receive this award. I hope in the future we shall receive more papers on telegraphic subjects. There is much work being done in telegraphy, but since Mr. Sidney Brown read his paper on cable relay work and other work on cable telegraphy we have had no paper of importance on telegraphy. We hope that the cable men and telegraph and telephone men in the Institution will remember that this Institution was founded as the Society of Telegraph Engineers, and that more papers dealing with those subjects will be sent in. We are able, according to our custom, to award a number of premiums besides those mentioned by name. We have got into the habit of calling these "extra premiums." Every year we have been able to award a number of such premiums, there being a number of papers of value, the merit of which the Council wished to recognise, so that they are not extra premiums in any sense other than that they have not at present any definite names. With regard to the Willans Premium, which we award alternately with the Institution of Mechanical Engineers, it may interest you to know that a Willans medal has been prepared, and that the large plaque reproduced in

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bronze from the original model, is to be seen in the Library of the Institution.

Perhaps the matter that will interest you most in the Report is the paragraph relating to the Institution building. Last June we had a special meeting in the building which will in a few days be the Institution of Electrical Engineers building, and you authorised the purchase of the building for a sum of £50,000. All the necessary financial arrangements have been made for completing the purchase. The large room along most of the front on the first floor will form the library. It is a very large, handsome, lofty room of about 3,000 sq. ft. area, very well lighted, facing the Embankment on the south. It will be one of the handsomest libraries possessed by any scientific or engineering institution in London, but it will not be at all too large for our great collection of books. It is proposed to enlarge and improve the entrance hall and the lecture theatre. The plans prepared by our architect, Mr. Percy Adams, are of a very satisfactory character. The theatre when completed will be about 30 per cent. larger than that of the Institution of Civil Engineers, where we have for so long had the privilege of holding our meetings. The remaining part of the building has been let for three years to the Royal College of Physicians and Surgeons. We are very glad that the whole of the parts of the building that we do not require for our own immediate needs will be occupied by the present owners. This is a mutually convenient arrangement to us and to the Colleges. We hope to move our offices into the new building in the autumn, but the theatre will not be finished until early next year. With regard to the British Electrotechnical Committee, I may say that since the Report was printed a meeting has been held, and Mr. Alexander Siemens has been appointed Chairman of the Committee in place of Sir John Gavey, who has resigned that position, but who remains on the Committee. You will notice that the Council have had under consideration the issue of a statement on the subject of professional conduct, a matter that we have had before us for some years. The Institution of Civil Engineers, which has always taken such a high standard on all matters of professional practice and conduct, in its recent Report issued a series of recommendations, which will no doubt be accepted as law by all the members of that Institution. We hope that a somewhat similar series of recommendations will be issued by this Institution before long.

Now that we have a building of our own, and a very handsome one, I feel sure members generally will recognise that the Building Fund is a fund to which they will wish to contribute. My own feeling is that the best way of increasing this fund would be, not so much by donations of large amounts from rich members of the Institution—although that is a mode which I am sure the Council would not discourage—but rather by every Member, Associate Member, Associate, and Student putting his hand in his pocket and contributing a small amount annually for a few years. I cannot help thinking that

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annual contributions by a large number of members of quite small sums annually would be the best way of showing that members generally appreciate the efforts of the Council in their work which has led to the acquisition of our very handsome building.

With regard to the Benevolent Fund, the Committee of Management has met when necessary and all applications have been considered. The work of benevolence has been carried on so far as seemed to be desirable. At present the Fund is small, and fortunately the number of applications is few, but we cannot expect that will always be the case. Later on the Fund is sure to have more demands made on it, and I commend it to your attention in the hope that it also may be added to regularly and readily by small annual contributions or otherwise.

Although it is not in the Report, I should like to mention a matter which has only been settled at the Council Meeting to-day. I mention it because I think you will like to hear of it, and because it is a matter in which I have particularly interested myself and have always kept in mind as a thing I should like to see carried out during my term of office. The Council has to-day sanctioned a pension scheme for the whole of the Staff. I will not go into details now; it does not come within the scope of the period dealt with by this Report; but I may say that the principle is this—that each officer or servant of the Institution contributes a certain proportion of the premiums necessary for a life assurance, the amount of which is settled by the Council. The Council contributes the balance of those premiums, so that in a sense the Council increases the salaries of all its Staff; but that increase goes, so far as this scheme is concerned, into the form of life assurance, to which the member of the Staff also contributes a certain proportion.

I do not know whether members sufficiently realise what a very valuable asset we have in the Library. It began, as you know, with the library left to the Institution under a certain Trust Deed by Sir Francis Ronalds, and it has been kept up, and is now being kept up perhaps more energetically than before. In connection with this work I ought specially to mention the efforts of Mr. Duddell, the Chairman of the Library Committee. Whatever Mr. Duddell undertakes he does with all his heart. When we get into the new building, and get the Library furnished and equipped, I believe members will be very much astonished to find what a magnificent Library the Institution possesses.

I now beg to move: "That the Report of the Council as presented be received and adopted, and that it be printed in the *Journal* of the *Proceedings*"; and I call on the Treasurer, in seconding the motion, to deal with the question of the Accounts.

Mr. R. HAMMOND: It gives me great pleasure to second the motion which has been moved from the chair. By the kindness of the members of this Institution I am put in the position of being a Chancellor of the Exchequer who every year enjoys a surplus. The Accounts that are before you show the very satisfactory result of not only a surplus, but a surplus which is an increase upon the surplus of the previous year. In order to arrive at the actual surplus you must add

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the balance which is to the credit of the General Fund, the balance that has accrued in the form of Entrance Fees, and the increment of the Building Fund, because if you do not do that the comparison is not on a proper basis. For instance, during the past year you will notice that, in view of the purchase of the lease of the building on the Embankment, we have transferred a number of securities from one Fund to the other, and therefore the interest accruing, which used to appear in the General Fund, this year appears in the Building Fund. The total of our increment, of our surplus, for 1908 is £5,174 17s. 5d., which compares with the surplus for the previous year of £4,909. We know that the industry is passing through a pretty strenuous time, and we are glad to feel that we can show, nevertheless, an increase in our surplus of £260. Just glancing back for a few minutes over a period of ten years, we have a very marked increase of prosperity shown by these accounts. In 1899 the total of the three increments for Entrance Fees, Building Fund, and General Fund was £1,443; in 1902 it reached £2,300. In that year we ventured to ask the members to increase their subscriptions, with the result that we immediately had an increase of revenue in 1903, bringing up our surplus to £4,486, while last year, as I have said, the amount stands at £5,174. Those who have studied the Accounts probably do not desire me to go into the details, because they speak for themselves, and those who have not studied them still less want anything said about them. I think, therefore, I will pass from the past to the future. In the years that are immediately ahead, when we get into the new building, the then Treasurer, whoever he may be, will not be in the position of coming to the Annual Meeting with a margin of £5,000 to the good. It is by having had these increases in the past and holding our hands somewhat that we have put ourselves into the position of acquiring our splendid building. Some have wondered why we ever bought the site in Tothill Street if we did not mean to build upon it. That is a story that has already been gone into; but at all events we have the site in Tothill Street, and at the right time it can be realised and the money, which in the meantime we have to borrow, repaid. With regard to the future, I am glad to be able to say that we shall enter the new building under conditions that enable us to say, in the first place, that we are quite confident that we are going to make both ends meet. Your Treasurer this time next year will, I feel confident, be in a position to state that he has not had to face a deficit, that we have been able to move into the new building with all its largely increased expenses, and still have a margin to the good at the end of the year. And more than that, he will also be able to say, I feel confident, that out of that margin to the good it has been possible to put aside a certain definite sum towards the extinction of the purchase price. I ask you to bear with me just for a few minutes further in order to explain how it is that I am able to be so cheerful to-night, in spite of the fact that on the 1st of June I have to draw a cheque for £50,000 on your account. The position is this. We have made arrangements with an Insurance Company for a loan on the annuity principle, which is repayable in any case in twenty-five years, and we also hope

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that in the new building, with its very charming rooms, as they will be, and its magnificent situation, we shall get an increased membership. The Institution does not always see eye to eye with the Treasurer as to the admittance of new members, because the Treasurer would like to see a thousand new members every year. The Members of the Council are taking greater and greater care to make the membership of this Institution something worth having, and therefore, though the financial instincts of the Treasurer would be in favour of admitting a larger number of members, the determination on the part of the Institution to make this at all events far and away the premier Electrical Institution of the world is to a certain extent keeping our revenue down. But, in spite of all that, I think we can say that our revenue in the new building will be increased.

The PRESIDENT: The Report is now open for discussion, and if any members wish to speak we should be very glad to hear them.

If no one wishes to make any observations, I will simply put the motion.

The motion was then put and carried unanimously.

The PRESIDENT: I now ask your permission to take as read the Auditors' Certificate of the Accounts, and to propose, "That the Statement of Accounts and Balance Sheet for 1908, of which copies have been sent to the members with the notice convening the meeting, be taken as read."

The motion was then put and carried unaminously.

The PRESIDENT: I now move, "That the Statement of Accounts and Balance Sheet for the year ending December 31, 1908, as presented, be received and adopted."

Mr. W. R. COOPER: I have much pleasure in seconding that.

The PRESIDENT: Do any members wish to make any observations on this subject? If not, I will put the motion.

The motion was then put, and carried unanimously.

The PRESIDENT: We have now the duty of passing certain votes of thanks, and I will ask Mr. Sparks to propose the first of them.

Mr. C. P. SPARKS: We must look back to-night some thirty-seven years to the original starting of this Institution, and remember that for that long period we have been materially assisted by the Institution of Civil Engineers and the Royal Society of Arts. Those two Institutions, and especially the Institution of Civil Engineers, have really acted as our parents; they have given us magnificent accommodation for no less than thirty-seven years, and I feel that our Institution has been largely built up, particularly by the efforts of the great engineering Society, the Institution of Civil Engineers. It is therefore my duty and very great pleasure to propose: "That the best thanks of the Institution be and are hereby accorded to the Council of the Institution of Civil Engineers and to the Council of the Royal Society of Arts for the great courtesy extended to the Institution by placing their rooms at its disposal for the holdings of its General Meetings."

Mr. LEON GASTER: I am very pleased indeed that the opportunity

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has been given to me to second this vote of thanks, and I have great pleasure in doing so.

The resolution was then put, and carried unanimously.

Mr. J. F. C. SNELL: It is my duty to propose the following resolution: "That the best thanks of the Institution be given to the local Honorary Secretaries and Treasurers abroad for their kind services during the past year."

Mr. G. F. MANSBRIDGE: I have much pleasure in seconding that.

The resolution was put and carried unanimously.

Mr. H. HUMAN: There is one honorary official of this Institution holding a very responsible position indeed, upon whom has devolved during the past Session very important work, and that is our Honorary Treasurer, Mr. Robert Hammond. In consequence of the prospective movement of the Institution to its new quarters on the Embankment, it has devolved on Mr. Hammond to draw up an elaborate statement with regard to the financial position of this Institution. In the course of events that Statement was brought under the notice of one of the leading lights in the actuarial world, and that gentleman remarked to me that it was a most admirable and lucid Statement, and that he could not help expressing his astonishment that an engineer of Westminster could draw up such a financial statement. I think it is a very great compliment to Mr. Hammond, and I feel sure as long as the purse-strings of the Institution are in his hands we may rest assured that our finances will be in a very sound condition. I have therefore very great pleasure indeed in moving: "That the best thanks of the Institution be given to Mr. Hammond in recognition of the valuable services rendered by him as Honorary Treasurer of the Institution during the past Session."

Mr. H. M. SAYERS: I have very great pleasure in seconding the motion. None of us here, I imagine, are surprised to hear of Mr. Hammond's financial ability. We have had a long experience of it, and know what he can do in that way; but I am sure you will agree with me that we ought to thank him very heartily for putting that ability gratuitously at the disposal of the Institution in the way he has done. I should like to say that I hope our Chancellor of the Exchequer next year will be the same as in the present year.

The resolution was put, and carried with acclamation.

Mr. R. HAMMOND: I should like to thank you very much indeed for passing this resolution. It is a great reward to me to feel that the work I have been called upon to do has been so heartily appreciated by you.

Mr. J. E. TAYLOR: I have much pleasure in proposing: "That the best thanks of the Institution be accorded to the Honorary Auditors, Mr. Sidney Sharp and Mr. R. S. Erskine, for their kind services during the past year."

Mr. L. T. HEALEY: I beg to second that.

The resolution was put, and carried unanimously.

Mr. A. H. WALTON: I have much pleasure in proposing a hearty

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vote of thanks to our Honorary Solicitors. We, as members of this Institution, especially the Council, value the advice they have given us during the past year. I therefore beg to move: "That the best thanks of the Institution be tendered to Messrs. Bristow, Cooke, and Carpmael for their kind services in their capacity of Honorary Solicitors during the past year."

Mr. J. W. JACOMB HOOD: I have much pleasure in seconding that.

The resolution was put, and carried unanimously.

The PRESIDENT: This annual passing of votes of thanks may appear to be a formal matter, but I am sure we all feel it is a very real one, and that our thanks are very sincere and genuine. We are infinitely obliged to the Institutions and persons who have helped the Institution of Electrical Engineers.

I have now to announce that, in accordance with the Articles of Association, the Council and honorary officers for the year 1909–10 are duly elected, no candidates other than those nominated by the Council having been put forward. The new officers are :—

President.

Dr. G. KAPP.

Vice-Presidents.

Sir H. H. CUNYNGHAME, K.C.B.	S. EVERSHED.
W. DUDDELL, F.R.S.	Col. H. C. L. HOLDEN, R.A., F.R.S.

Members of Council.

W. W. COOK.	Major W. A. J. O'MEARA, C.M.G.
G. K. B. ELPHINSTONE.	W. H. PATCHELL.
DR. E. HOPKINSON.	J. H. RIDER.
J. W. JACOMB-HOOD.	W. RUTHERFORD.
W. JUDD.	J. F. C. SNELL.
Professor T. MATHER, F.R.S.	G. STONEY.
W. M. MORRISON.	A. H. WALTON.

C. H. WORDINGHAM.

Associate Members of Council.

E. RUSSELL CLARKE. | H. HUMAN.

J. E. TAYLOR.

Honorary Treasurer.

ROBERT HAMMOND.

Honorary Auditors.

H. ALABASTER. | SIDNEY SHARP.

The chair was then taken by Mr. C. P. Sparks, Vice-President, and the remainder of the evening was occupied in the reading and discussion of a paper (see page 618) by Mr. W. M. Mordey, President, entitled, "Some Tests and Uses of Condensers."

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At a Special General Meeting of Members, Associate Members, and Associates, duly convened and held at the Offices of the Institution, 92, Victoria Street, Westminster, S.W., on Thursday, July 29, 1909—Mr. W. M. Mordey, President, in the chair.

The Secretary read the notice convening the meeting.

The President: We have now reached a very important stage in connection with our new building on the Victoria Embankment.

On June 30th last year at a Special General Meeting authority was given for the purchase of the property for a sum of £50,000. This purchase was duly completed on June 1st this year, the purchase money being provided as follows:—

From the accumulated funds of the Institution	£24,000
From a mortgage on the building	26,000
	£50,000

Ever since the meeting of June 30th last year, the Council have been engaged on the consideration of various schemes for adapting the building to the purposes of the Institution, and they have finally decided that it would be in the best interests of the Institution to enlarge and improve the entrance hall and to rebuild the theatre completely. Plans prepared by our architect, Mr. Percy Adams, have been considered, and finally the specifications have been issued and tenders obtained for these alterations. The result is that an expenditure estimated at £18,000 is necessary to cover these alterations in the building, and the equipment, and furnishing of the large library on the first floor, and of the parts of the building to be occupied by the Institution, including also the cost of a lift and various other matters necessary to adapt the other parts of the building to the requirements of our tenants.

The new theatre will be a very handsome one, appreciably larger than that of the Institution of Civil Engineers, in which we have for so long had the great privilege of holding our meetings. The modified entrance hall will provide a very attractive and convenient means of access to the theatre, library, offices, and public rooms.

The funds of the Institution would be sufficient for the purpose of the required expenditure if we sell the Tothill Street site at the price we gave for it—viz., £17,500—a price which we are advised is a low one. It is believed that when the time is more favourable we shall be able to dispose of the site at a profit.

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Meantime we have arranged for—

A mortgage on the Tothill Street property, of	£11,500
And have securities available amounting to ...	4,000
A total of ...	£15,500

As already explained—

The estimated expenditure is about	£18,000
And, adding for contingencies and margin ...	2,000
We require a total of ...	£20,000
We are therefore short to the extent of about ...	£4,500

The sale of the Tothill Street property at cost price would, after paying the mortgage off, yield about £6,000. To meet this expenditure of £4,500, and to justify the Council in putting before the members a recommendation to proceed with the proposed alterations, the past and present Members of the Council have guaranteed the difference between the assets and the requirements, on the understanding that if they are called upon to make any payments under this guarantee they are to be repaid out of the funds of the Institution when available, either as a result of the sale of the Tothill Street property, or from contributions to the Building Fund, or otherwise.

Two resolutions are before you; the first is necessary to meet the wishes of the Economic Life Assurance Society, from whom we have borrowed a sum of £26,000 on the security of the new building; the second is a resolution approving the proposed expenditure.

The PRESIDENT then moved the following resolution :—

"That the action of the Council in borrowing the sum of £26,000 from the Economic Life Assurance Society on the security of the leasehold property of the Institution on the Thames Embankment on the terms of the indenture of mortgage dated June 1, 1909, a copy of which is now produced to the meeting, be and is hereby authorised and confirmed."

The resolution was seconded by Mr. R. KAYE GRAY, Past-president, and, on being put to the meeting, was carried unanimously.

The PRESIDENT then moved :—

"That an expenditure of a sum not exceeding £20,000 on structural alterations, furniture, and fittings in connection with the Institution Building be sanctioned and approved, and that the Council be authorised to make such financial arrangements (including the borrowing of money on the security of the Institution Building and of the Institution property in Tothill Street) as the Council may consider necessary for the above purpose."

The resolution was seconded by Mr. R. HAMMOND, Honorary Treasurer, and, on being put to the meeting, was carried unanimously.

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OBITUARY NOTICES.

ALEXANDER ADAMS died at Glasgow on November 29, 1908. He was born at Dundee in 1863, and at an early age entered the Navy, where he was employed on torpedo work, and incidentally acquired a good knowledge of electrical wiring. He then took up wiring work for the Woodside Electrical Company, and for Messrs. Mavor and Coulson, and a few years later joined the Electricity Department of the Glasgow Corporation on its formation in 1892. He was rapidly promoted until he became mains superintendent in 1896, which position he held until the time of his death. He effected many improvements in the details of main laying, and was most energetic and painstaking in the discharge of his duties. He was elected an Associate Member of the Institution in 1900.

WILLIAM EDWARD AYRTON, F.R.S., who died on November 8, 1908, at the age of 61, was the son of a well-known barrister, and was educated at University College, London, where in 1867 he obtained first place in the examination for the Indian Government Telegraph Service. After studying electrical engineering for a short time under the late Lord Kelvin, he went out to India to take up the post of assistant electrical superintendent of the Telegraph Department. In 1871 he was promoted to the position of superintendent, and in 1872 came over to England to assist in the manufacture of the Great Western telegraph cable, under Lord Kelvin and Professor Fleeming Jenkin. In 1873 he went to Tokio as Professor of Physics and Telegraphy at the Imperial College of Engineering, but in 1879 he returned to England and was for a time Professor of Applied Physics at Finsbury Technical College, and in 1884 was appointed Professor of Electrical Engineering at the Central College, Exhibition Road, which position he retained up to the time of his death.

Much of his scientific work was done in collaboration with Professor Perry, who went out to Japan in 1875 as Professor of Engineering. Their joint investigations gave rise to many important discoveries in the theory of electrical science and its practical applications. They devoted special attention to electrical meters, many of which were brought out before the need for them had arisen, and they were awarded prizes at the Paris Exhibition of 1889 for the almost complete series they exhibited. They also acted as joint engineers to the Faure Accumulator Company, and carried out the electric lighting of the Grand Hotel, Charing Cross, in 1883. They designed a surface contact railway with automatic signalling, and (with Professor Fleeming

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Jenkin) a system of electric telpherage, and in these also they were rather ahead of the requirements of that period.

Professor Ayrton was a Fellow of the Royal Society, and the recipient of the Society's "Royal Medal" in 1901 for services to electrical science. He was President of the Mathematical and Physical Section of the British Association in 1888, and of the Physical Society in 1890. He was Honorary Treasurer of this Institution from 1897 to 1902, and was President in 1892. He wrote many valuable contributions to the literature of the science, including an excellent treatise on "Practical Electricity," and his personal instruction has proved valuable to many of his pupils by inciting them to active research. He was gifted with impetuous energy, originality of thought, and great courage in the face of difficulties.

He married in 1885 Hertha, daughter of Levi Marks, well known for her researches on the electric arc, and the only lady member of the Institution.

EBENEZER JOHN BRISTOW died at his residence, North Side, Clapham Common, on December 29, 1908, after a short illness. He was nearly 84 years old, having been born at Exeter in January, 1825. Early in life he came to London to study law, and was admitted a solicitor in 1847. Three years later he became a partner in the firm of Harrison and Wilson, of 1, Copthall Buildings, E.C., which subsequently became the firm of Wilson, Bristows, and Carpmael, who have been Honorary Solicitors to the Institution from its foundation. On the death of his brother he was elected to membership in 1902 as the representative of his firm, of which he had been senior partner since 1870.

He was for some years a member of the Incorporated Council of Law Reporting for England and Wales. He was also for over thirty years a member of the Council of the Incorporated Law Society, and was President in 1883–4. He married in 1851 the daughter of Mr. Samuel Griffin, of Portsmouth, who survives him with a son and daughter.

W. P. J. FAWCUS died in London on March 28, 1909. For some time his health had been bad, and while recovering from a surgical operation he contracted a severe chill which developed into a fatal attack of pneumonia.

Mr. Fawcus took a prominent part in the early development of the electrical industry in this country. He served articles with Messrs. Hall, of Dartford, and was subsequently for some years at the works of Messrs. Thorneycroft & Co., Chiswick. In 1887 he put forward a scheme for electric lighting at Chester, and also established a water-power lighting station at Keswick, the first of its kind in this country. Later he became managing director of the Manchester Edison & Swan Company and while there carried out the electric supply of Altrincham. In 1898 his company was absorbed by the Edison & Swan United

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Electric Light Company, and he was given a place on the board, and also became managing director of Messrs. W. T. Glover & Co. He was elected an Associate Member of the Institution in 1899, and in 1907 was transferred to the higher class. He was also for some time a member of the Council, and was President of the Northern Society of Electrical Engineers, of which society he was practically the founder. He was a firm believer in the future of South Africa, both for agriculture and engineering, and spent a few years in that country shortly before his death.

THOR PEDER K. HAMMARSKJOLD died on January 18, 1909, from typhoid fever, at the early age of 36. He was born in 1873, at Stockholm, and in 1899 came to London to join the British L. M. Ericsson Manufacturing Company, of which he was managing director at the time of his death. He was elected an Associate Member of the Institution in 1902, and was also a member of the Swedish Chamber of Commerce.

CHARLES GEORGE HAMPSON died in August, 1908, after several months' illness. He was for over seven years in the employment of the Lahmeyer Electrical Company, of New Oxford Street, London. He was particularly identified with the introduction of electricity into mines, and in this connection was well known to many of the leading colliery managers in South Wales.

He was elected an Associate Member of the Institution in 1905.

HUGH ERAT HARRISON died on August 12, 1909, at the age of 50. He was born at Westminster in 1859, and educated at University College, London, where he gained an exhibition and took honours in experimental physics. He was for a time with the Anglo-American Brush Company, and the Hammond Electric Light and Power Company, Sheffield, and organised for the latter firm an electrical engineering college in Red Lion Square, London. In 1885 this was closed, and he became a partner in the firm of Phillips, Harrison, and Hart. In 1889 he organised and founded the Electrical Standardising, Testing, and Training Institution, Faraday House, Southampton Row, which he carried on up to the time of his death. He organised a Testing Department, and was made Board of Trade Inspector for several towns. He was also an examiner to the Board of Education, and was one of the delegates sent by the Institution to the International Congress at St. Louis in 1904.

In the early days of Faraday House, Mr. Harrison used to give a complete course of about seventy lectures on electrical engineering. He began with electrostatics, and gradually developed the whole subject in a clear and lucid manner. He spent much thought in simplifying algebraical proofs, and was fond of illustrating physical laws by graphic methods. He had a high opinion of Faraday's "Experimental Researches," and in a pamphlet entitled "Opsigraphics" applied

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the conception of Faraday tubes to the simple solution of many problems. His laboratory skill was acquired from Professor Carey Foster, and he used often to follow the Socratic method of asking his students simple questions in order to make them think for themselves.

Mr. Harrison became an Associate of the Institution in 1881, and a Member in 1886. He was twice elected on the Council, where his services proved most valuable. He was possessed of a singularly clear judgment, and was a man of strong character.

HAROLD THORNTHWAITE HINCKS, whose death occurred on January 21, 1909, was born at Chester on May 10, 1873, and received his education at the King's School, Chester, and the Chester College of Science. He was for a short time with Messrs. Fawcus and Cowan, at Keswick, and afterwards became a pupil in the Liverpool Corporation Electrical Department, and with Mr. H. E. Taylor, of Chester. From 1894 to 1898 he was chief assistant to the Sandycroft Foundry, Hawarden, and from 1898 to 1906 was electrical engineer to the Kolar Gold Field Syndicate in various capacities, finally becoming resident electrical engineer, and having charge of stations supplying 60,000,000 units per annum. In 1906 he was appointed station superintendent, and later chief engineer, of the North Wales Power and Traction Company, but shortly before his death he had taken up an appointment with the Electrical Company, Charing Cross Road, London.

He was elected an Associate Member of this Institution in 1901.

ELEUTHÈRE ELIE NICOLAS MASCART, who died on August 25, 1908, at the age of 71, was a native of Quarouble, in the North of France. He was educated at Valenciennes and at the Ecole Normale Supérieure, Lille, where he finally graduated in 1864. He held various professorships in physics both there and at Metz and Versailles, and acted as deputy for the celebrated Régnault at the Collége de France. On Régnault's death, in 1872, he succeeded to his chair. He early showed a capacity for dealing methodically with the details of meteorology, and in 1878 was appointed director of the Central Bureau of Meteorology in Paris. He held this position until 1907, and during his term of office he succeeded in perfecting the organisation of the department and establishing the systematic publication of weather charts and forecasts.

His early researches were mainly in optics, and later his attention was devoted to electricity, magnetism, and the measurement of electrical quantities. He was awarded the Prix Bordin for his work on spectrum analysis and the determination of wave-lengths. He also investigated in great detail the subjects of dispersion and interference, and examined the question whether it was possible by optical phenomena to determine the absolute motion of a body without any reference to that of the earth. His conclusion was that optical phenomena indicate only the motion relative to the earth, and for this result he was in 1874 awarded a Grand Prix.

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In 1876 he published an excellent treatise on statical electricity embodying Green's theory of potential and Lord Kelvin's electrometric work. About this time he also studied certain electrical effects in meteorology. In 1877 he published articles on the theory of electrodynamic machines, and correctly stated the law of efficiency of motors, which up till then had not been generally understood. He carried out experimental work in connection with M. Angot, and obtained very accurate results in the measurement of electrochemical and other units.

In 1884 he was elected to the Académie des Sciences, and held various positions in that distinguished body, becoming President in 1904. He was also President of the Société Française de Physique and of the Société Internationale des Electriciens. He was created Grand Officer of the Legion of Honour for services to his Government during the Franco-German War in connection with the making of explosives at Bayonne. In 1885 he was made an Honorary Member of the Physical Society of London; in 1892, Foreign Member of the Royal Society; and in 1901, Honorary Member of this Institution. His health broke down soon after he resigned his post as Director of Meteorology. He only lived a year after his retirement.

EMIL NAGLO died somewhat suddenly at Berlin on September 12, 1908, from heart disease, after being indisposed for several months. He was born on February 25, 1845, at Laurahutte, in Silesia, but when quite young went to Berlin. He served articles of apprenticeship with Messrs. Siemens and Halske, remaining with them as an assistant in the cable-making and laying departments. In 1872, with his brother as partner, he set up in business as Naglo Brothers, with two workmen and very small premises. The business grew rapidly, in spite of the many difficulties which the firm had to face owing to the keen competition then existing in the electrical trades. The firm carried out, among other works, the electricity undertakings at Blankenburg and Königsberg (5-wire system), and the circular railway at the Berlin Exhibition. The business was amalgamated in 1897 with that of Messrs. Schuckert Brothers, now the Actien Gesellschaft.

Mr. Naglo was an original member of this Institution, and was also a member of the Elektrotechnischer Verein, of which he was twice president and several times chairman.

ARTHUR WARREN K. PEIRCE died at Driehoek, in the Transvaal, on June 14, 1909, as the result of ptomaine poisoning followed by malarial fever. He was only 36 years of age, and at a period of his professional career as an electrical engineer when he appeared to have a brilliant future before him.

He was a native of America, but came early to South Africa, and at the age of 25 was consulting electrical engineer to the Consolidated Gold Fields, and general manager of the General Electric Power Station. When this latter company was absorbed by the Victoria Falls

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Power Company, he continued with them as superintendent in charge of the Germiston and Brakpan stations.

He was elected an Associate Member of the Institution in 1907.

FREDERIC AUTEN COMBS PERRINE died at Plainfield, New Jersey, on October 20, 1908. He was born on August 25, 1862, and was educated at the Freehold Institute, New Jersey, and at Princeton University, where he graduated D.Sc. in 1885, and M.A. in 1886. His education was on very broad lines, and having taken up the study of science, he continued to extend his knowledge by habitual reading almost to the time of his death. He specialised in electrical engineering, and on leaving college was some years with the United States Electric Lighting Company, of New York, and with John A. Roebling's Sons' Company, and for a short period with the Germania Electric Company, of Boston. On the winding up of this company, he gave up engineering practice, and began his more successful work of teaching, being appointed Professor of Electrical Engineering at Stanford University, California. Before taking up this work he acted as a judge, and as a member of several committees, at the World's Fair, Chicago.

Dr. Perrine in organising the department at Stanford University endeavoured as far as possible to combine the mathematical and physical theory of electricity with its practical applications to engineering in the workshops and elsewhere. His success was largely due to personal contact with his students, and to informal discussions with them supplementary to the ordinary lectures. During the latter part of his connection with the University he was also chief engineer of the Standard Electric Company, of California.

In 1904 he resigned both positions to become president and general manager of the Stanley Electric Manufacturing Company, of Pittsburg, Mass., and in 1904 he resigned this post to take up private practice, which he continued to the time of his death.

He held positions for a short period as editor of two technical papers, and belonged to many important societies. His connection with this Institution, as Member, dates from 1903.

ROBERT PORTELLI died at Malta on March 30, 1909, at the age of 68, after a severe attack of pneumonia lasting only a few days.

He was for the greater part of his life in the service of the Eastern Telegraph Company, on whose staff he became a superintendent. He established, in 1881, at his own expense, the telephone service of the Island of Malta, with exchanges at Malta and Gozo ; and later on, at the suggestion of the military authorities, linked up the system with the Military Telephone Service. During the cholera epidemic of 1887 he gratuitously provided telephone communication at the isolation hospitals.

In 1896 the late King Humbert conferred on him the distinction of Knight of the Order of the Crown of Italy. He was elected an Associate of the Institution in 1874, and a Member in 1886.

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JOHN RANCE, JUN., died at Deal on September 16, 1909, after an illness lasting several months. He was born in 1868, and was educated at the United Westminster Schools. He held scholarships at the Finsbury Technical College and the City and Guilds of London Institute, and obtained a free pupilage with the Anglo-American Brush Electrical Engineering Company, subsequently remaining with them as assistant. In 1894 he was employed by Messrs. Johnson & Phillips to erect transmission plant at the Sheba Gold Mines, in Rhodesia; and this proving successful, he erected similar plant at Pahang, in the Malay States, and at the Raub Australian Mines. He was appointed chief electrical engineer to Messrs. Jessop & Co., Calcutta, in 1905, and remained with them until February, 1909, when he was compelled to return home owing to his health having given way.

He became an Associate of the Institution in 1889, and was transferred to membership in 1897. In its early days he contributed much useful help to the Students' Section.

CHARLES HENRY REYNOLDS, C.I.E., died in May, 1908, at Lisbon, where he was attending the International Telegraph Conference as delegate of the Pacific Cable Board. He was the son of an officer in the Indian army, and was born at Ootacamund on January 15, 1844. He was educated at University College, London, where in 1867 he obtained the first place in the Final Examination, and subsequently was given a special course of training at Glasgow University, under Lord Kelvin. He then proceeded to India to take up an appointment in the Telegraph Department. In 1870 he was appointed personal assistant to the Director-General of Telegraphs, and after passing through all the higher appointments of the Department, became Director-General in 1875. In 1899 he retired, and two years later was appointed general manager to the Pacific Cable Board, which position he held until the time of his death. He was an original Member of the Institution, and was in 1885 one of the representatives of India at the International Telegraph Conference at Berlin, and was made a companion of the Order of the Indian Empire in 1897.

NORMAN RHEAM was born in Liverpool on August 28, 1863. He was educated at private schools, and served his time from 1885 to 1888 in the works of Messrs. Crompton & Co., Chelmsford. On its completion he was for nine months head of the firm's test-room, and also assisted in the installation of electric light on some of the P. & O. Company's vessels. He was next employed in erecting and running electrical plant in the Transvaal, and later acted in the same capacity for Messrs. Thomas Cook & Sons in Cairo. On returning to England in 1891 he was appointed assistant engineer on the City and South London Railway Company, being promoted in 1896 to the post of chief assistant engineer. He superintended, under the chief engineer, Mr. P. V

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McMahon, the construction of new buildings, the erection of plant, and the equipment of the line. Subsequently he had charge of the maintenance and repairs of the locomotives, and of repairs in the power house, sub-stations, and permanent way. His death took place in London on February 15, 1908, at the age of 44. He was elected an Associate Member of the Institution in 1900, and was transferred to Membership in 1902.

WILLIAM WINSTANLEY STRODE died on January 30, 1909, after only a few hours' illness. He was head of the firm of Strode & Co., which was founded a hundred years ago by his grandfather, and was foremost in the lighting and heating industry in all its different stages. Mr. Strode, after being educated at Brighton College and on the Continent, was left in charge of the business at the age of 18 by the death of his father, and began active duties three years later. At that time the firm were specialists in gas-lighting plant both in England and abroad. In 1881, however, on a visit to the Paris Electrical Exhibition, Mr. Strode was greatly impressed by the new illuminant, and from that date he gradually abandoned the gas-lighting work and took up electrical engineering instead. Numerous public and private engineering installations in this country and on the Continent testify to his practical abilities.

He was one of the pioneers of the Electrical Contractors' Association, which had for its object the raising of the general standard of work. He was also an enthusiastic supporter of the Volunteer movement, and served twenty-seven years in the London Scottish Volunteers. He was elected an Associate of the Institution in 1888, and was in 1899 transferred to the class of Associate Members.

DOUGLAS LEWIS KNEVETT WELLS, whose death occurred at Brussels on November 20, 1908, was the eldest son of the late Mr. Lewis Wells, traffic accountant of the Eastern Telegraph Company. He was for ten years in the service of the Associated Telegraph Companies, and did considerable work both in laying and repairing cables for colonial and foreign Governments. Afterwards he went into practice as a consulting electrical engineer, and in this capacity he acted for several foreign Governments. He finally settled at Brussels, holding the agency for a number of English firms.

He was elected an Associate of the Institution in 1888, and was transferred to Membership in 1891.

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EXPLANATION OF ABBREVIATIONS.

[P] signifies a reference to the general title or subject of a Paper.

[*p*] signifies a reference to a subject incidentally introduced into a Paper.

[D] signifies a reference to remarks made in a Discussion upon a Paper, of which the general title or subject is quoted.

[*d*] signifies a reference to remarks incidentally introduced into a discussion on a Paper.

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